Beam-Propelled Lightcraft and Lightsails: Latest Developments

by

Prof. Leik N. Myrabo
Rensselaer Polytechnic Institute
Troy, NY 12180-3590

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PRESENTATION OUTLINE

I. Microwave Lightcraft Developments (sponsored by MSFC):
 - Animation of Lightcraft launch by National Geographic for TV documentary, "The Quest for Space."
 - Discussion of "rip-stop" SiC thin film, inflatable tensile structure (two 5-10 mil face sheets in sandwich).
 - Design of ultra high power density rectenna by CRC.
 - Air-Spike Experiments at RPI in hypersonic shock tunnel.

II. Laser Sail Experiments (sponsored by JPL/ NASA):
 - 5-cm diameter carbon microtruss sails manuf. by ESLI.
 - Tests used 150-kW LHMEL CO2 laser at WPAFB.
 - Review of Dec. '99 pendulum deflection tests.
 - Latest Dec. '00 vertical wire-guided flight tests.

HI. Laser Lightcraft Flights at WSMR (sponsored by FINDS)
 - New World altitude record of 233-ft, set on 2 Oct. 2000.
 - Flights employed Lightcraft model #200-5/6, with several design improvements.
 - The 50-gm aluminum Lightcraft models sustained no damage in 13-second long flights, and will fly again.

Part I

Microwave Lightcraft Developments
(Sponsored by NASA/ MSFC)

Animation of Lightcraft launch by National Geographic for TV documentary, "The Quest for Space."

Discussion of "rip-stop" SiC thin film, inflatable tensile structure (two 5-10 mil face sheets in sandwich).

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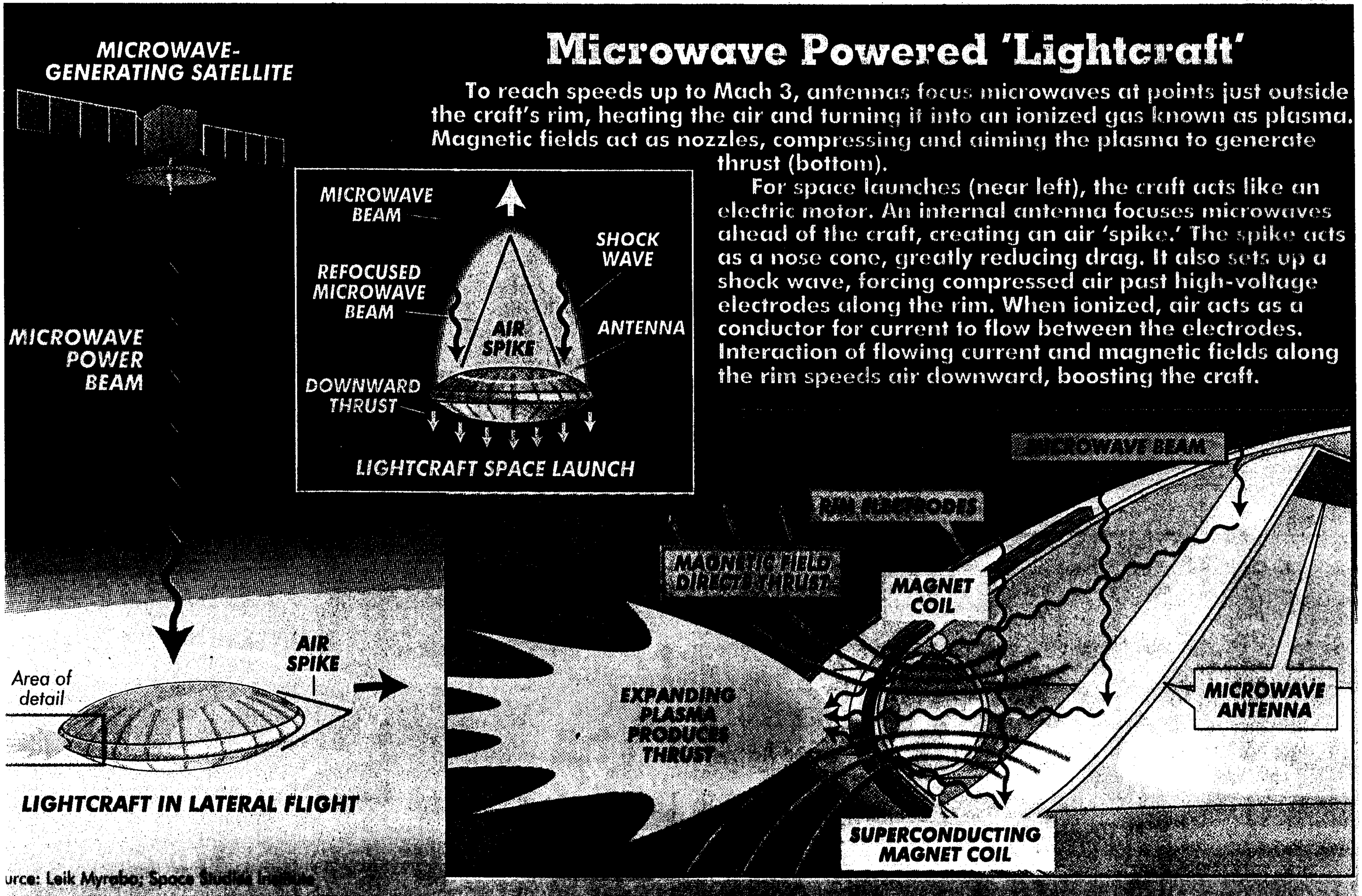
DAVE HERRING – ST

Microwave Powered 'Lightcraft'

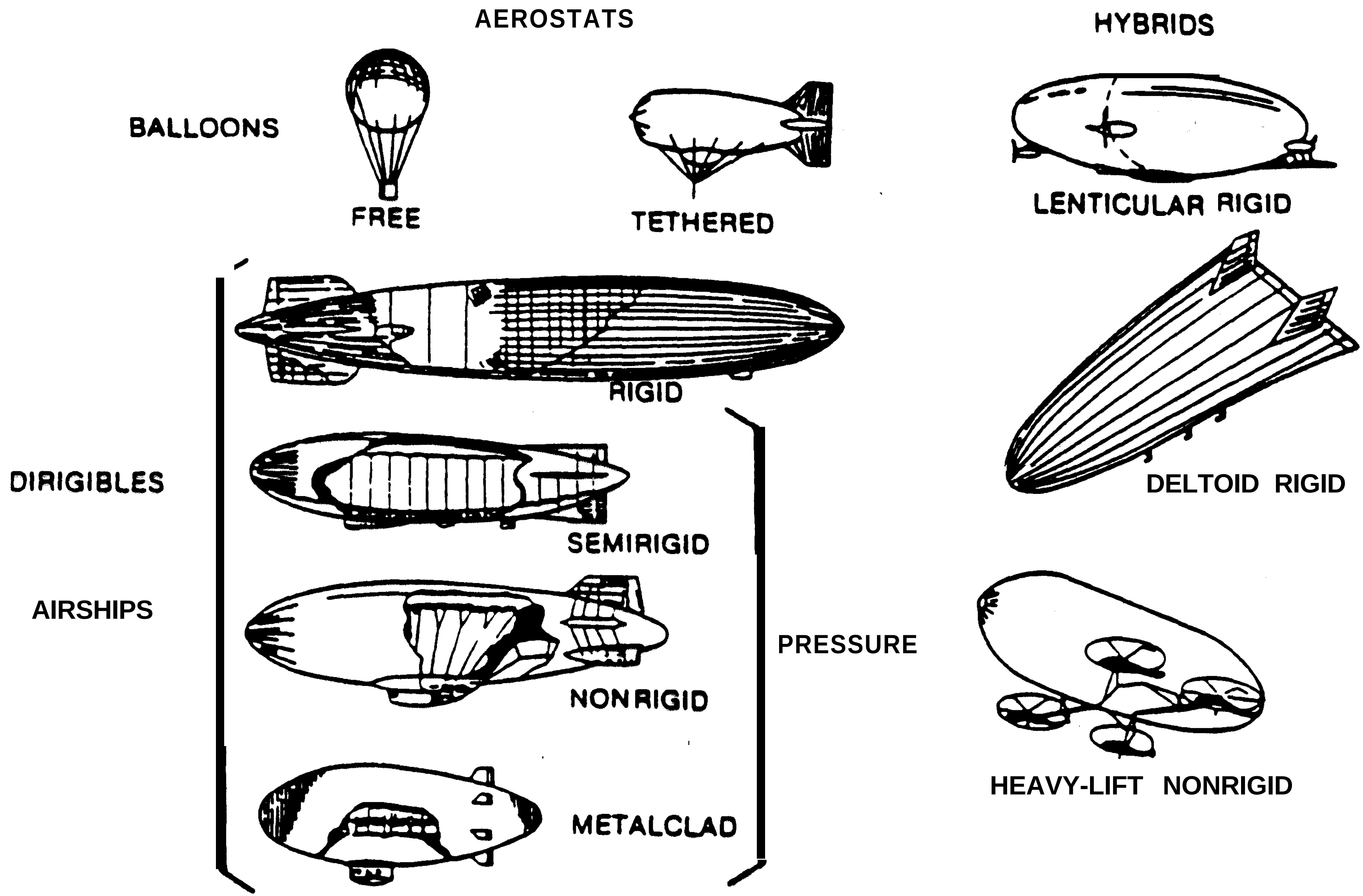
To reach speeds up to Mach 3, antennas focus microwaves at points just outside the craft's rim, heating the air and turning it into an ionized gas known as plasma. Magnetic fields act as nozzles, compressing and aiming the plasma to generate thrust (bottom).

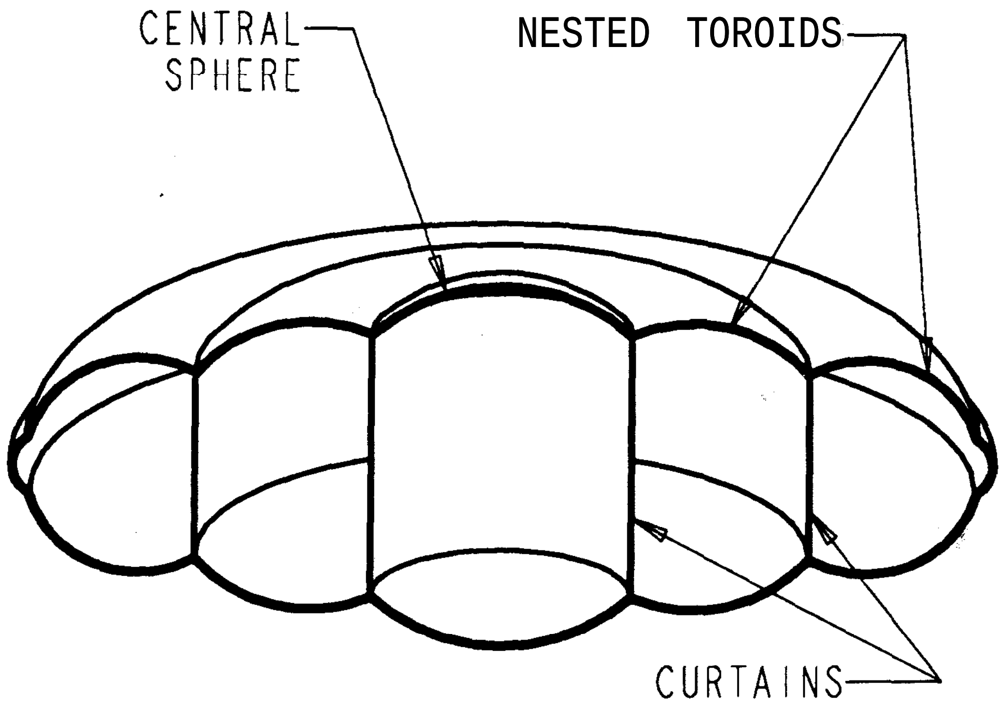
For space launches (near left), the craft acts like an electric motor. An internal antenna focuses microwaves ahead of the craft, creating an air 'spike.' The spike acts as a nose cone, greatly reducing drag. It also sets up a shock wave, forcing compressed air past high-voltage electrodes along the rim. When ionized, air acts as a conductor for current to flow between the electrodes. Interaction of flowing current and magnetic fields along the rim speeds air downward, boosting the craft.



urce: Leik Myrabo; Space Studies Institute

TYPES OF LIGHTER-THAN-AIR AIRCRAFT




CENTRAL
SPHERE
NESTED TOROIDS
CURTAINS

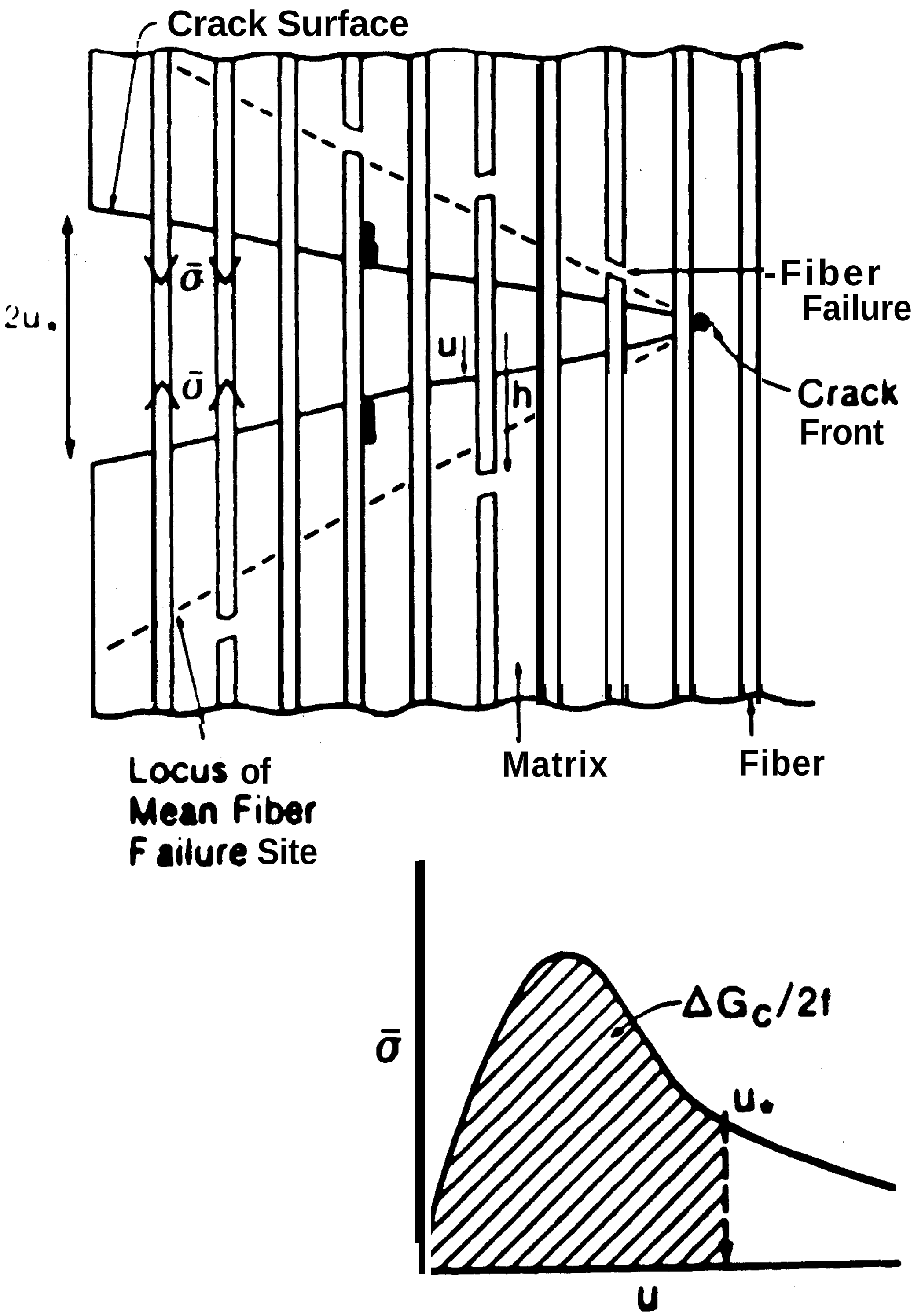
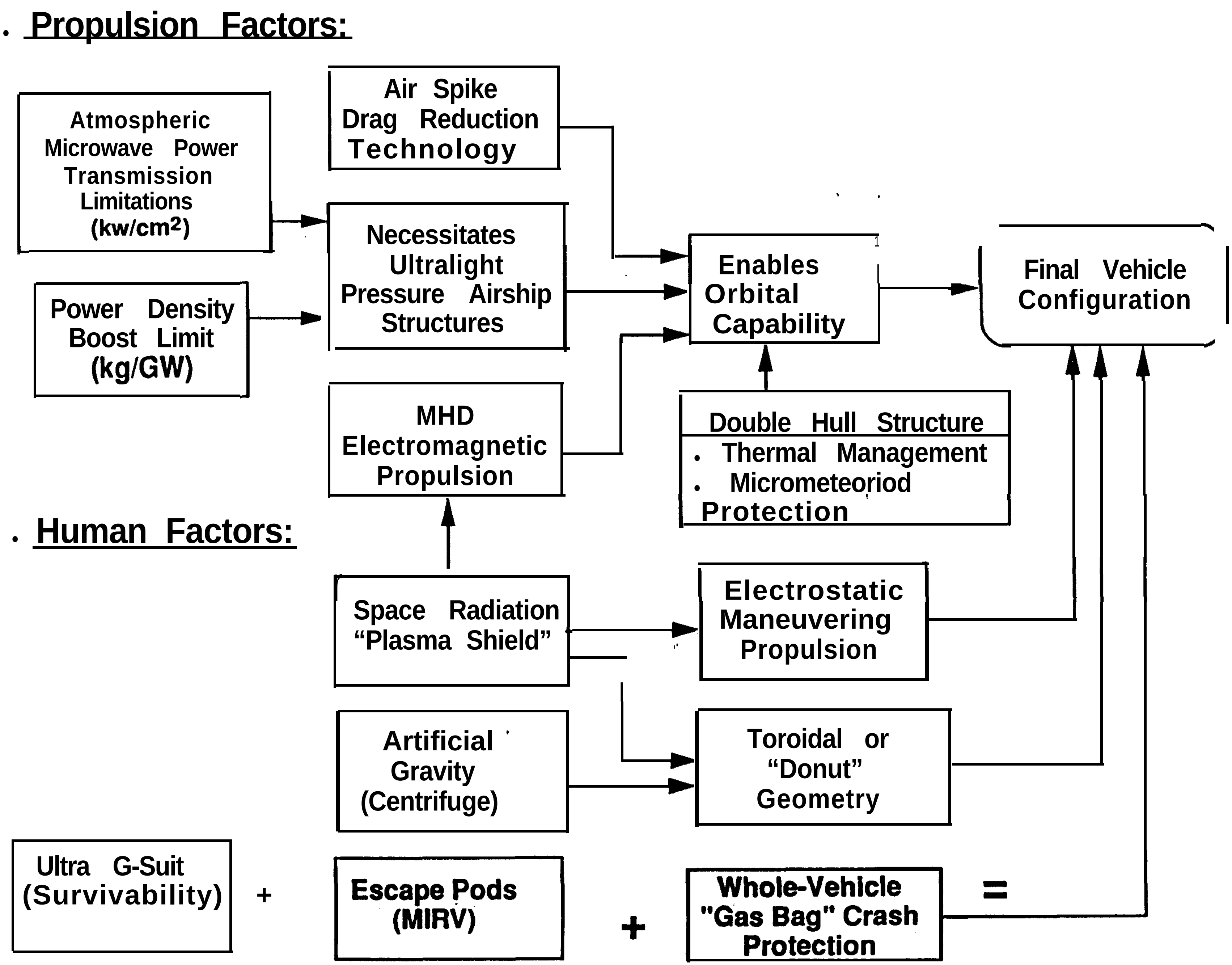
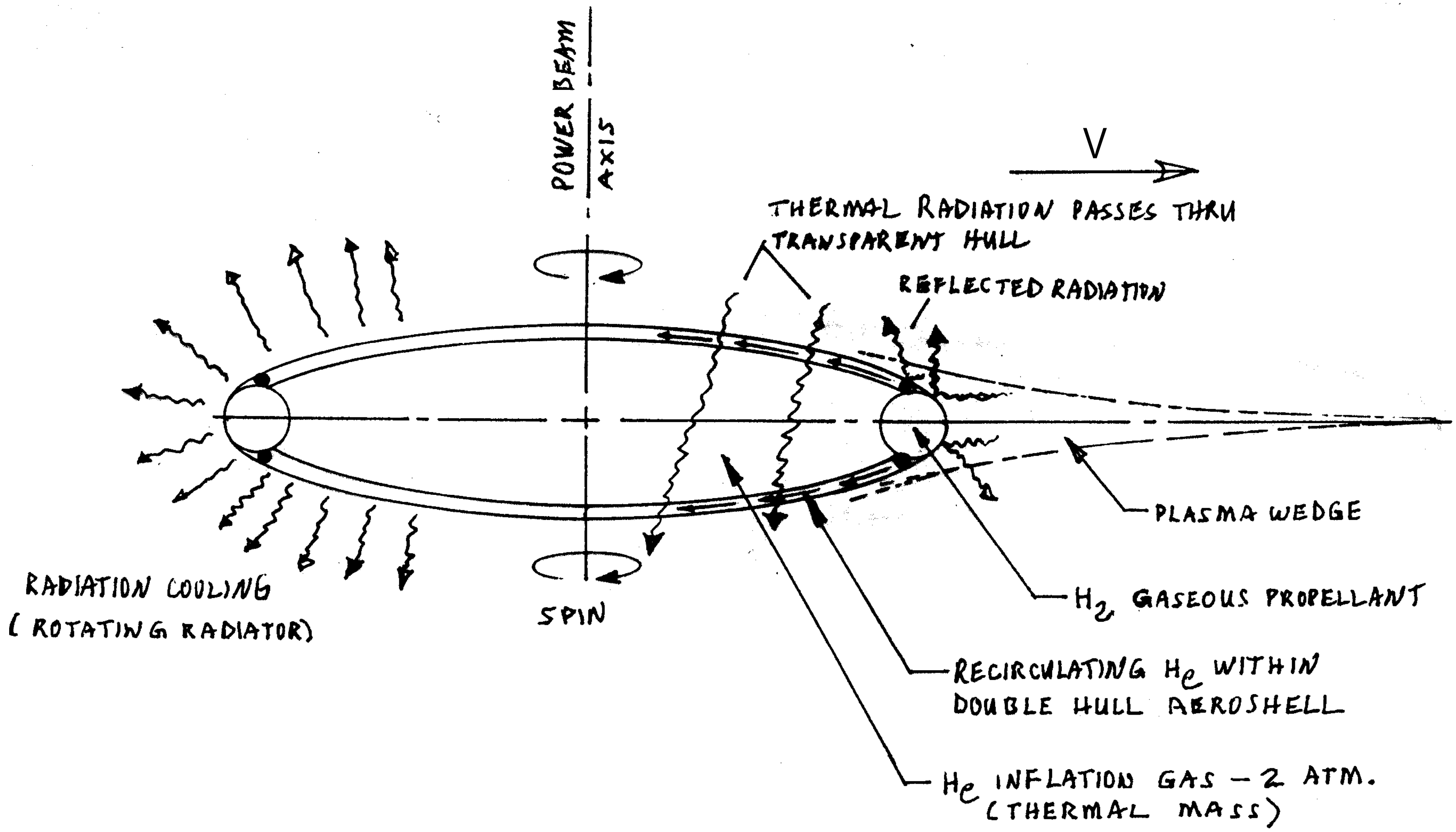


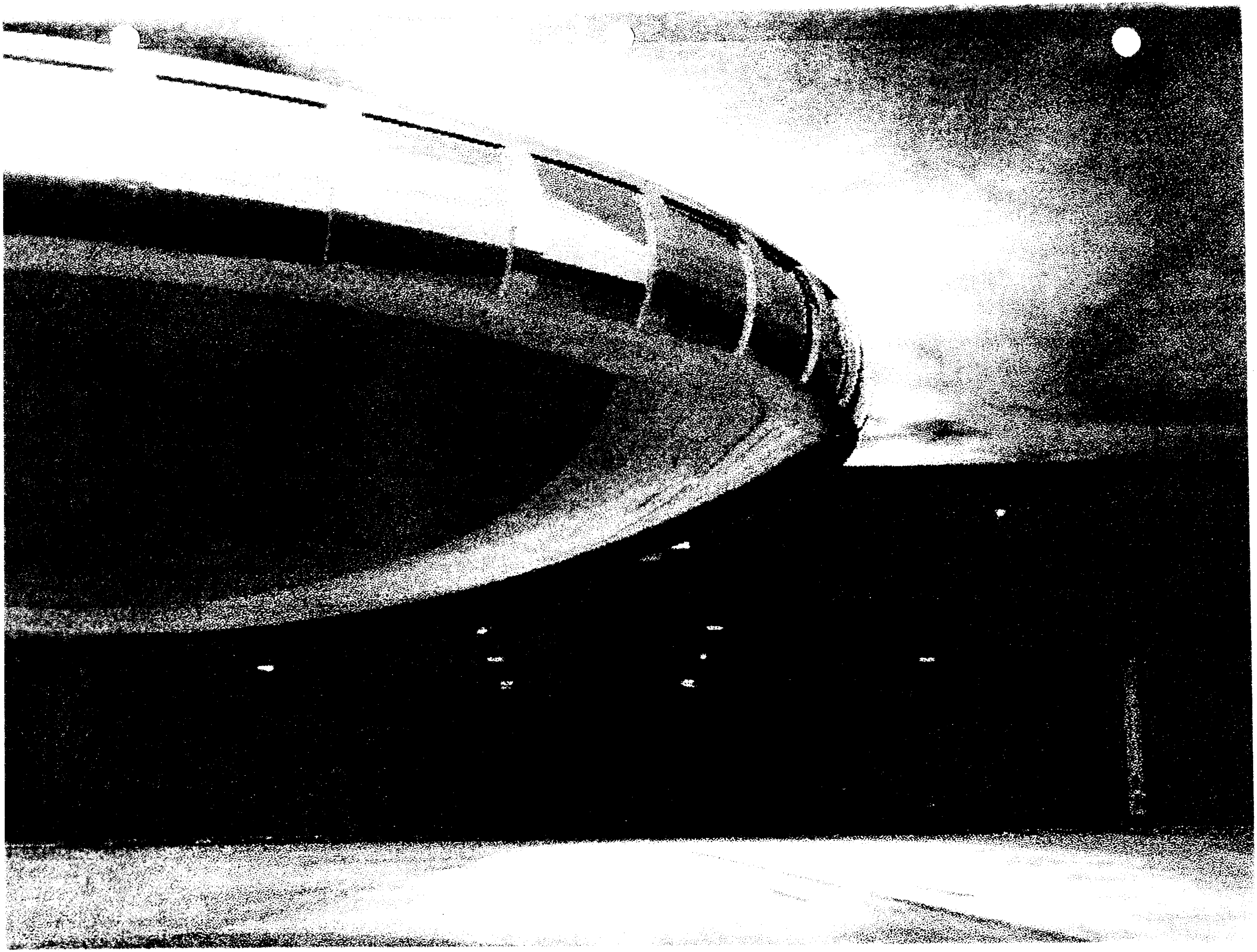
Fig. 1. A schematic indicating crack bridging by intact and fractured fibers. Also shown is the locus of the mean fiber failure sire and a typical variation in crack surface traction $\bar{\sigma}$ with crack opening, u, that governs the fracture resistance, AG,.

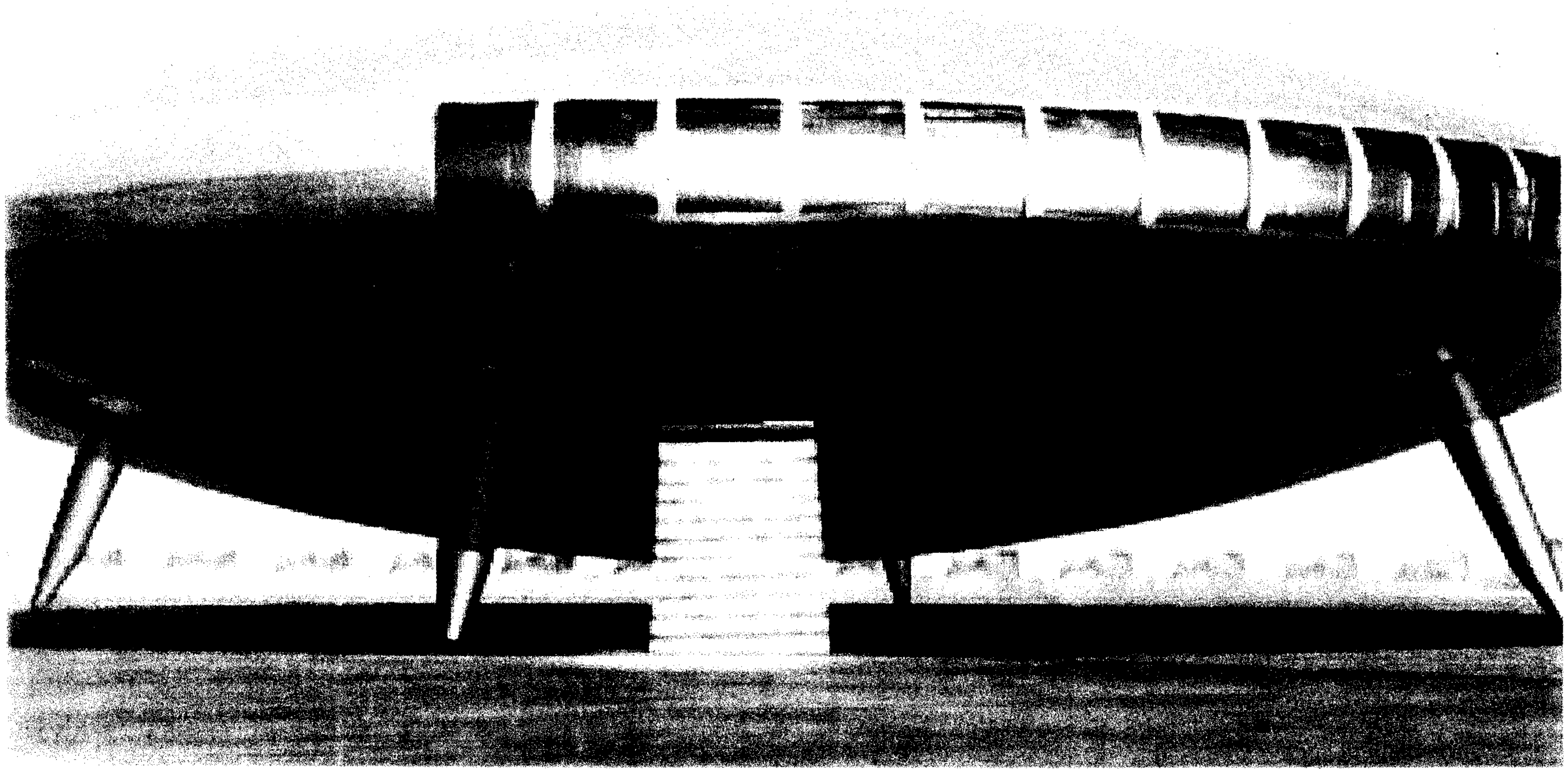
FUNCTIONAL ANALYSIS

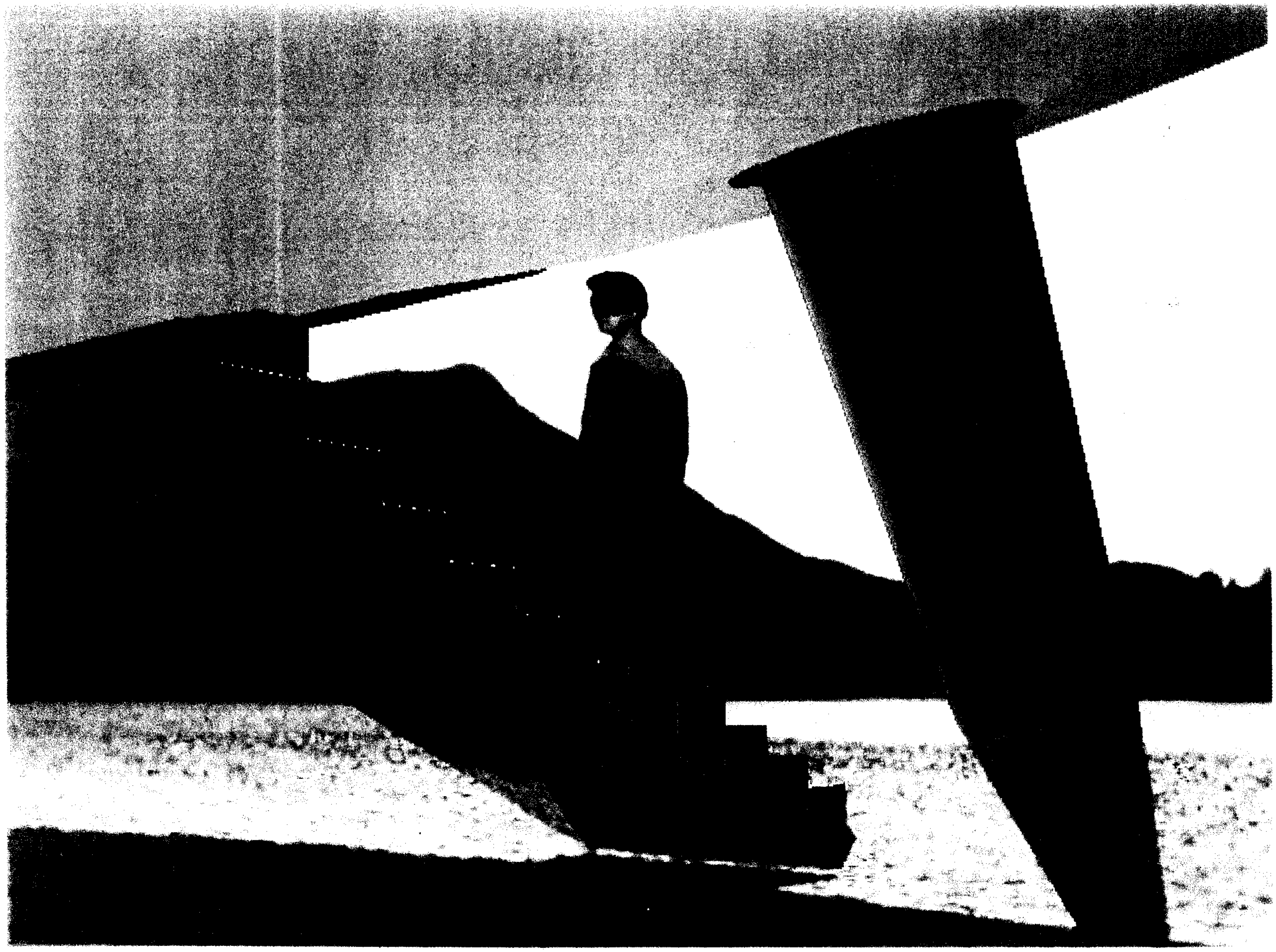


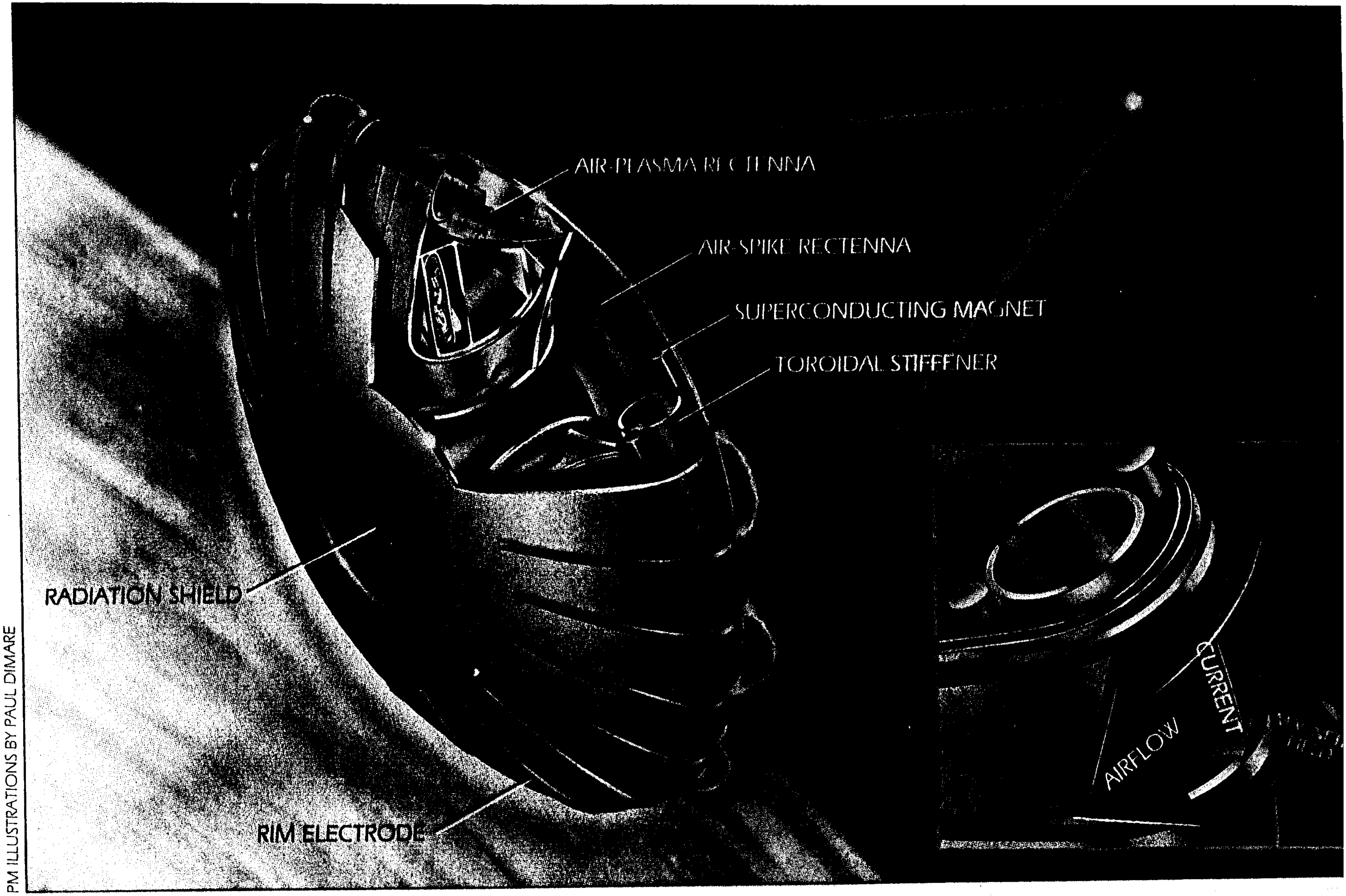
THERMAL MANAGEMENT (LATERAL FLIGHT)







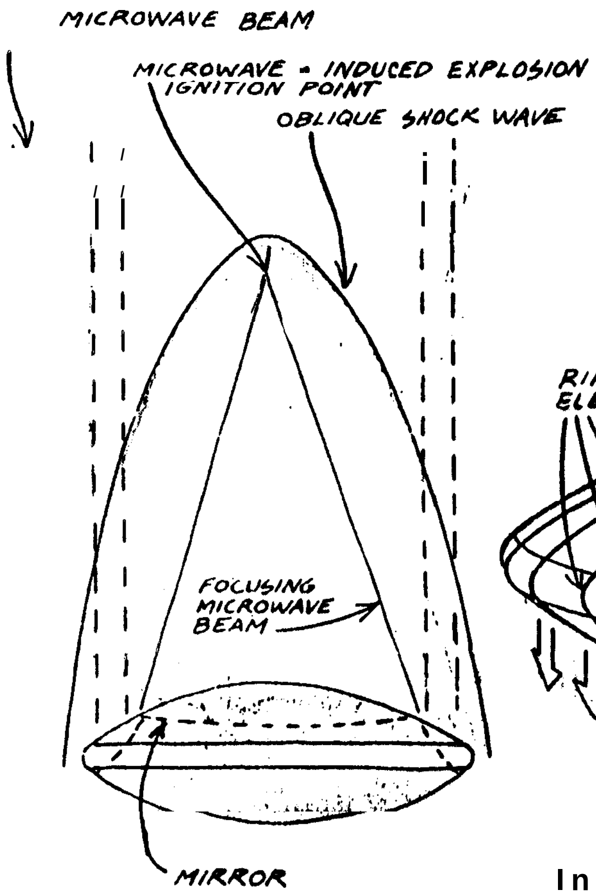




PM ILLUSTRATIONS BY PAUL DIMARE

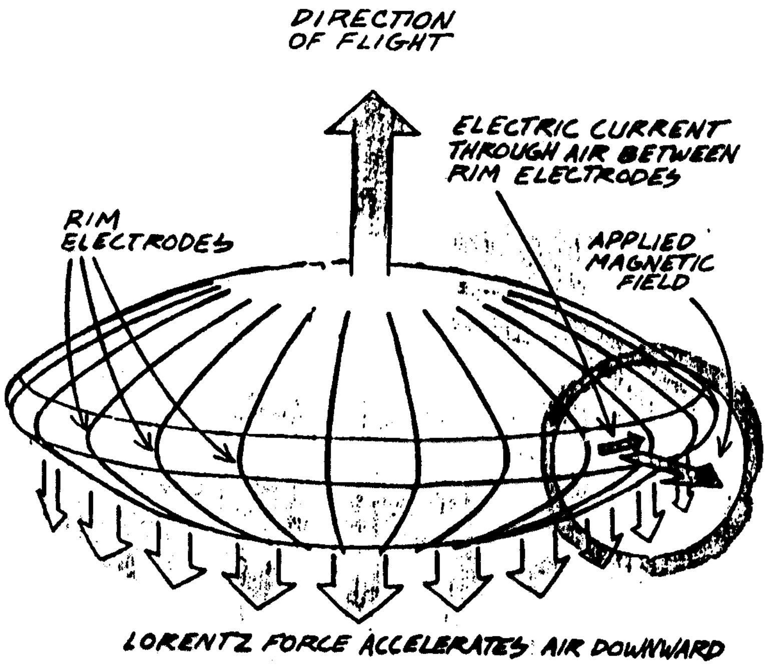
Mi-rowave 'Beam Rider' Propulsion System Ele-ents

• "Air Spike" inlet



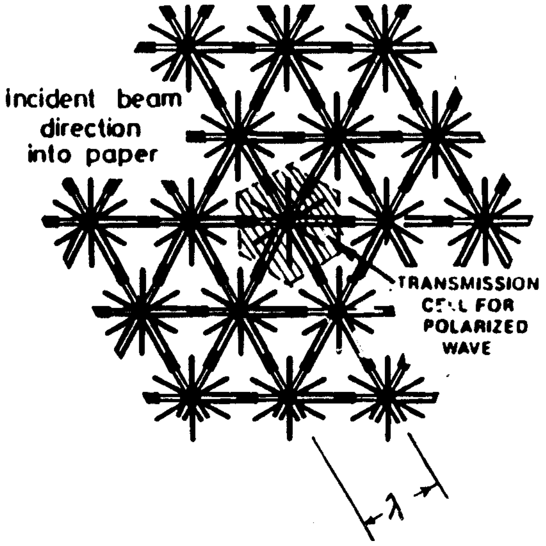
Focused microwaves shape bow shock wave ahead of ship to act as an inlet spike for the MHD Fanjet.

• MHD-Fanjet



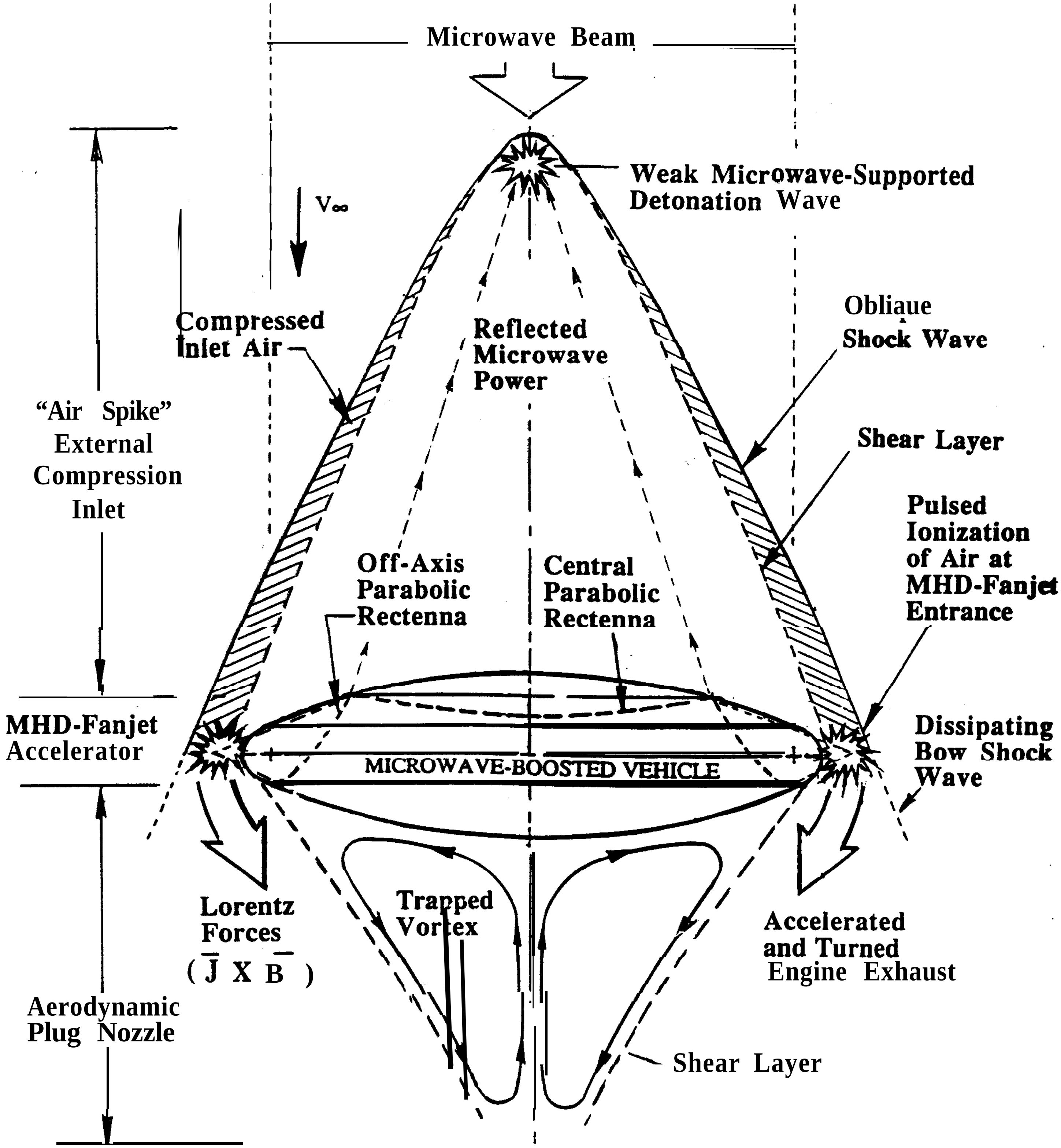
In hypersonic flight, externally - powered Lightcraft uses magnetohydrodynamlc effect to accelerate air past Its hull.

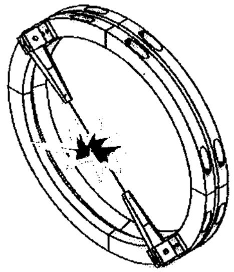
• Rectifying Antenna



Microwave beam energy is converted to electricity by large rectifying antenna (85% efficient) for MHD Fanjet.

Integrated Engine/Vehicle Design

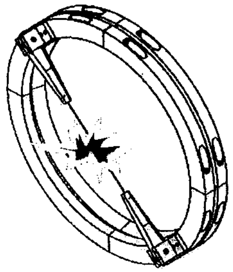




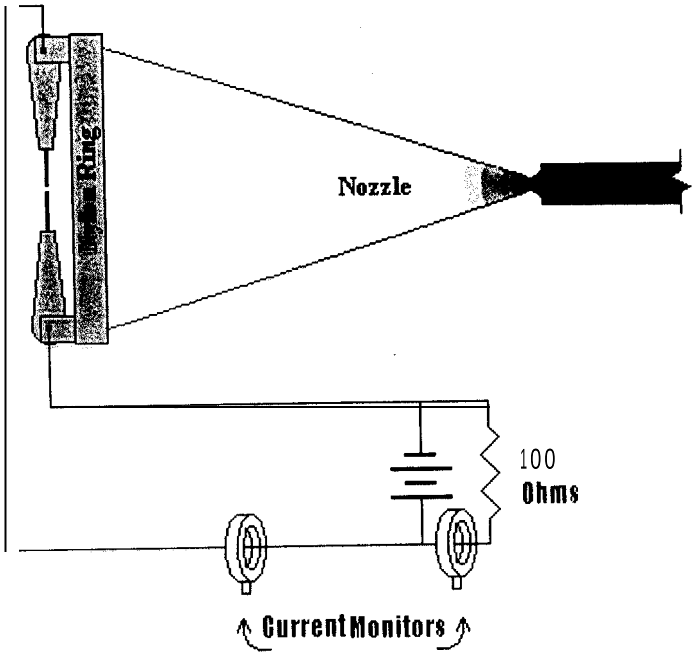
Purpose and Goals

- CONCEPT
  - Drag on a blunt body in hypersonic flow can be reduced by adding energy to the flow ahead of the vehicle.
  - This energy can be beamed ahead of the vehicle using a focused laser or microwave beam.
  - With upstream power addition, the oblique Air-Spike shock wave replaces the normal shock wave, thereby decreasing drag.

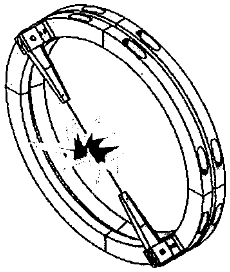
- PRESENT WORK
  - An electric arc is used to simulate the addition of power ahead of the blunt body in Mach 10 flow.
  - CFD density gradient predictions match the experiment well and match roughly 25% of the input electric arc power.



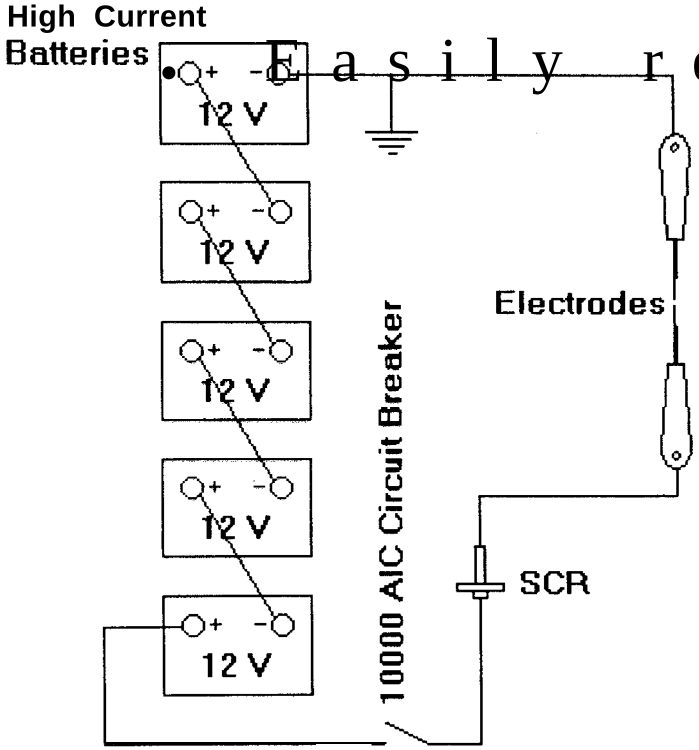
Electric Arc Apparatus



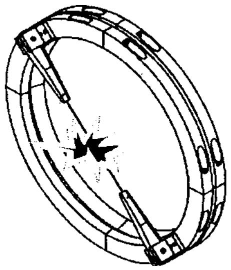
- Two variable geometry, 1/ 16” Zirconiated Tungsten electrodes.
- Nylon ring surrounding nozzle exit for mounting copper terminals.
- Five to ten “beefy” 12.6 V lead-acid batteries in series provide high-current discharges for each test.
- Two Pearson current monitors dynamically measure current and voltage supplied to the arc.



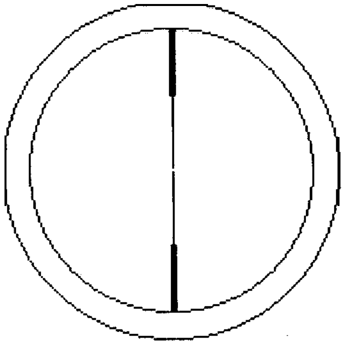
DC Battery Array



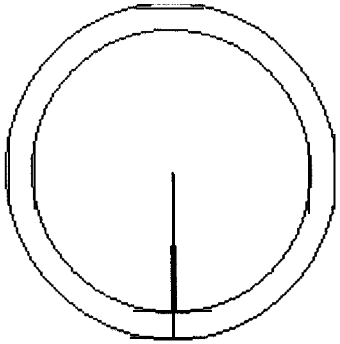
- Easily reconfigurable, from 1 to 10 batteries in any series or parallel combination thereof.
- Ten batteries can produce voltages of up to 126 Volts (in series), or maximum currents over 10,000 Amps (in parallel).



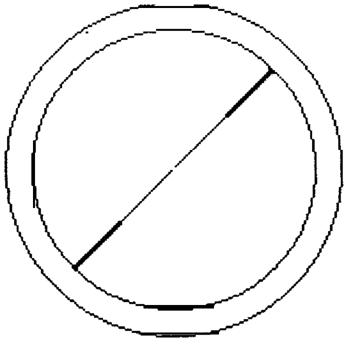
Electrode Arrangement



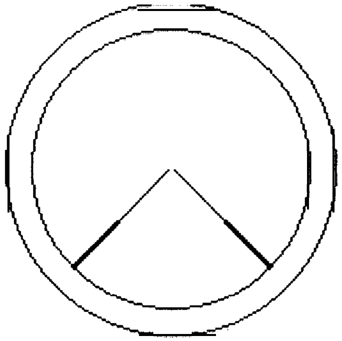
1) 0 deg. 180 deg



2) 0 deg. single electrode

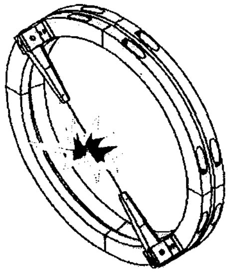


3) 135 deg. -45 deg

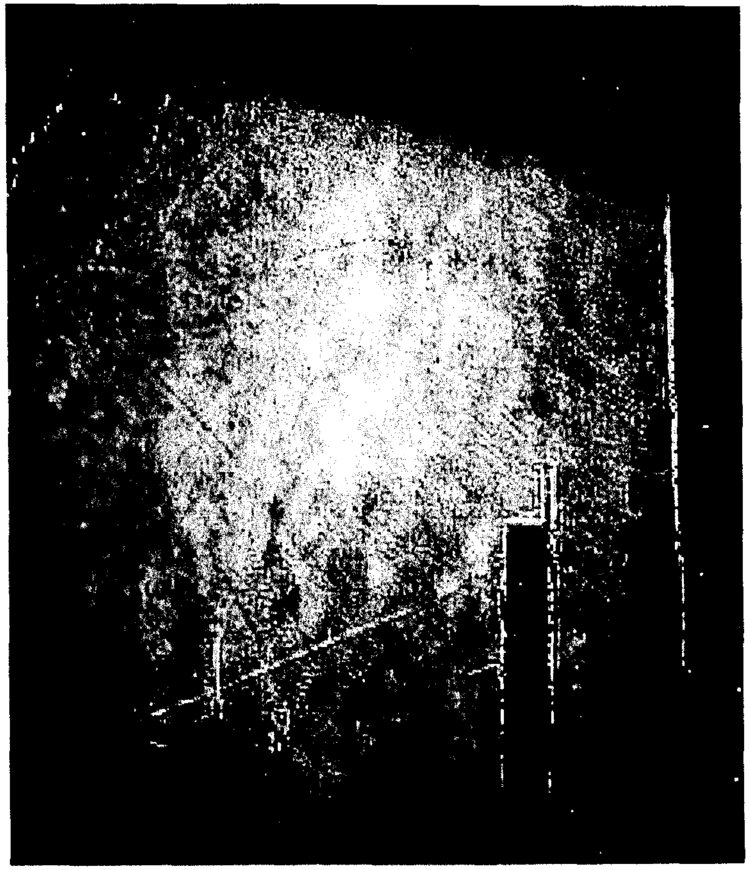


4) 45 deg. -45 deg

- Several electrode arrangements have been tested with and without the blunt body installed.
- The most successful to date has been the +/- 45 degree arrangement.
- With the blunt body installed, early schlieren photos reveal that the wake from the +/-45 electrodes interferes with the formation of the normal shock wave across the body.

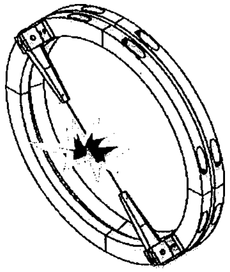


Experimental Results: Electric Discharge in Mach 10 Flow

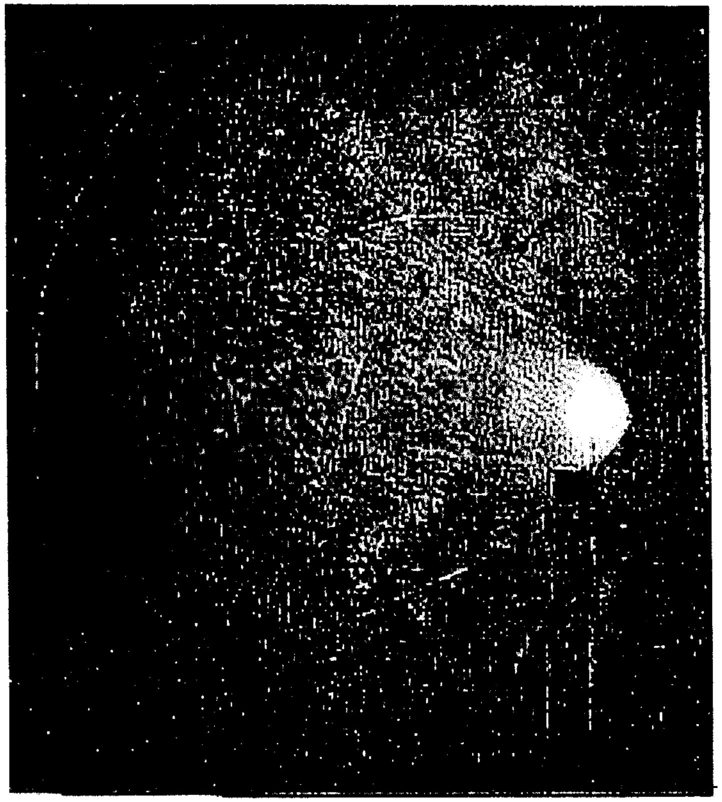


27 kW without blunt body

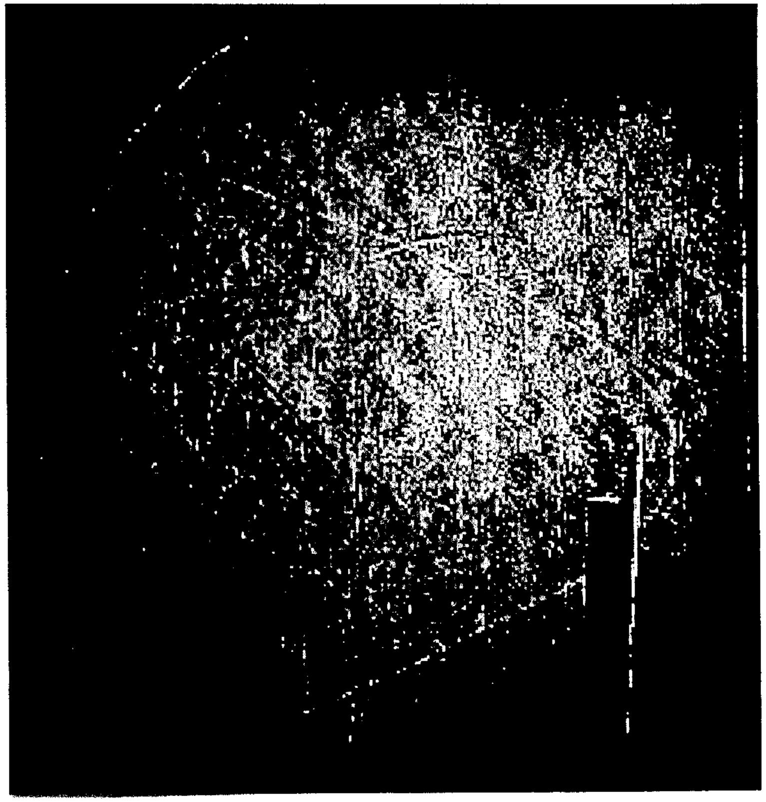
- DC power supply provided a low noise power source for arc discharges.
- Discharge was initiated by an SCR and cut off when the I^2t exceeded the inline circuit breaker limits.



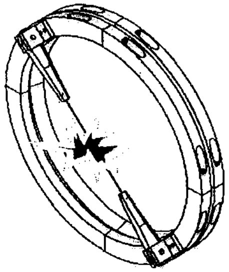
Experimental Results: Electric Discharge in Mach 10 Flow



47 kW without blunt body or narrow-band filter



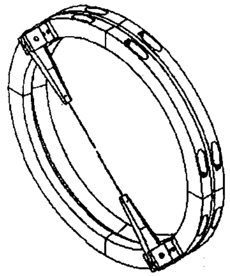
62 kW without blunt body



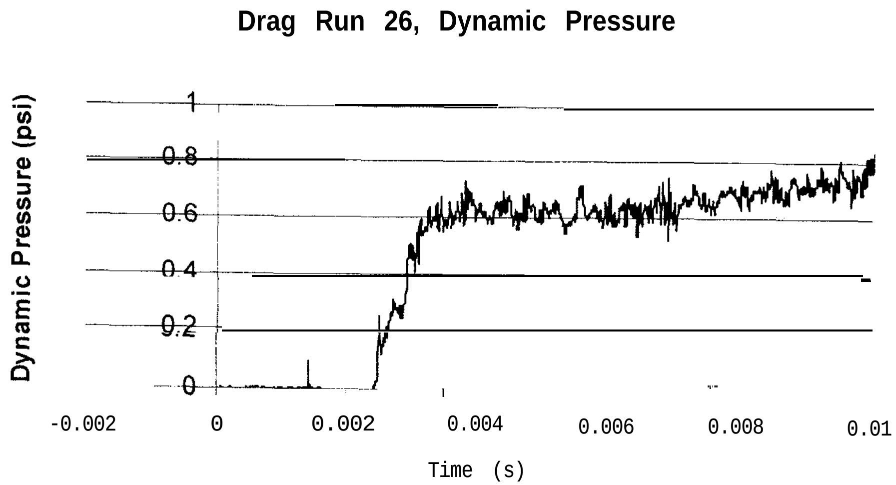
Experimental Results: Electric Discharge in Mach 10 Flow

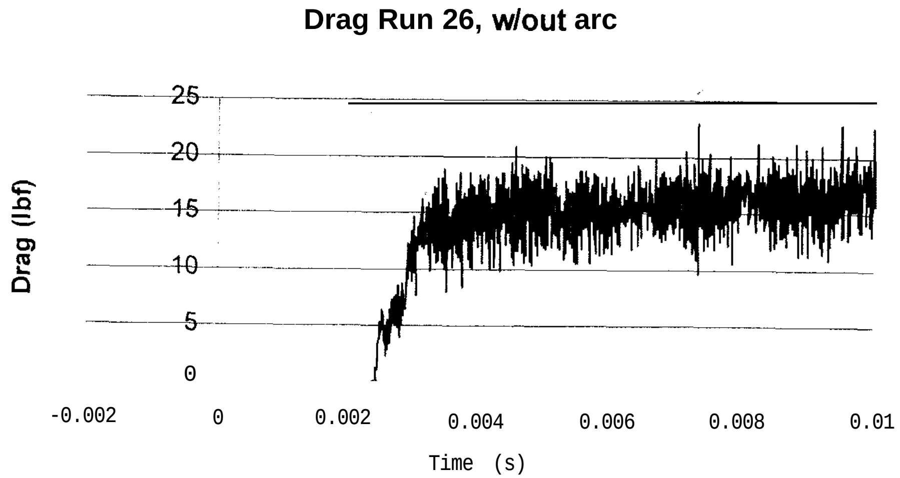
27 kW with blunt body 11.2 cm behind arc.

27 kW with blunt body 9.1 cm behind arc.

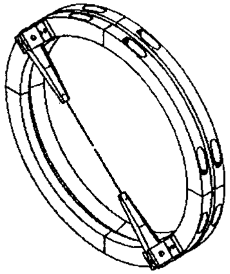


Unpowered Drag/Pitot Pressure Comparison



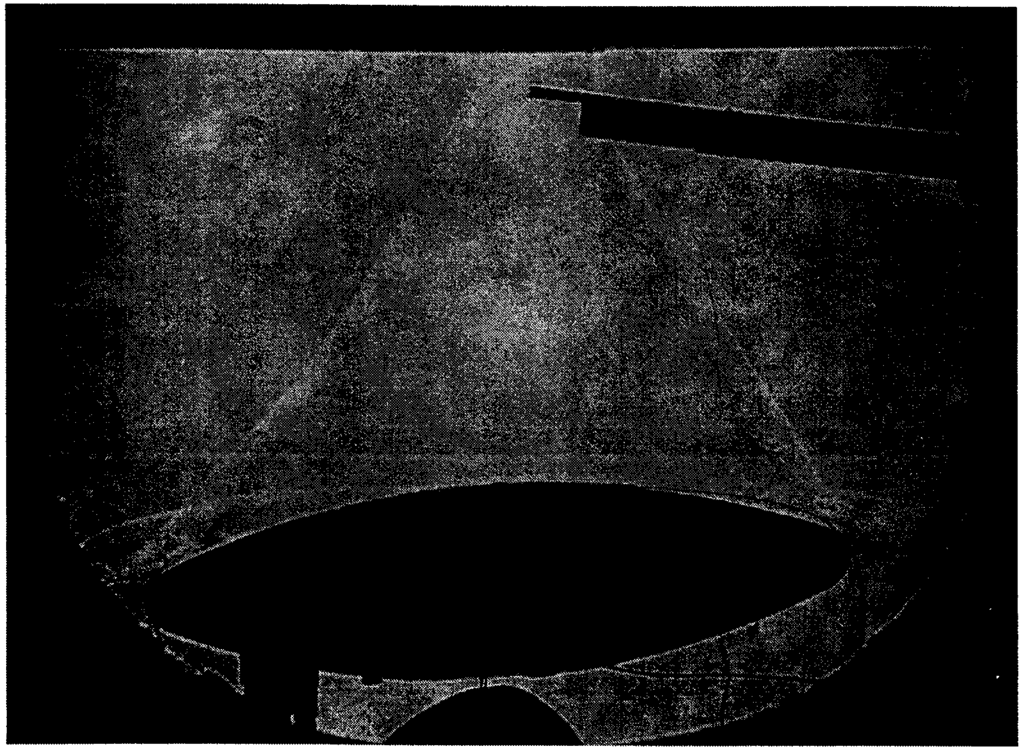


- Drag trace closely resembles dynamic pressure trace.
- Using D=QSCd, these results yield an average drag coefficient of .92.
- Accelerometer/mass system reacts quickly to changing flow conditions (even catches flow establishment).

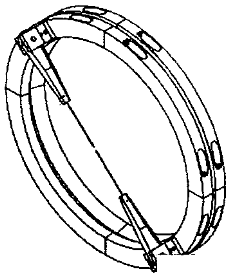


Measured Air-Spike Drag and Power:

First Captured on 22 March 2001

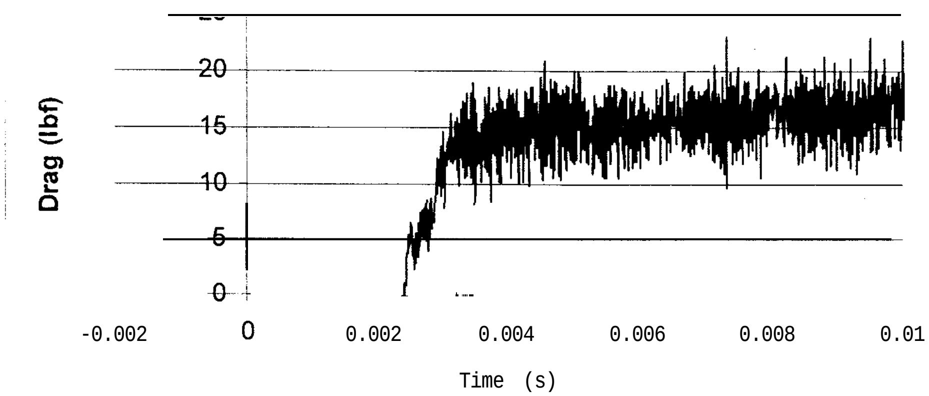


- Arc strikes 1 ms before flow establishment.
- Obvious reduction of drag while power is on.
- Complicated arc/flow interactions exist.
- Therefore only general trends can be extracted from this data.
- Blunt body is slightly tipped due to crude prototype alignment system

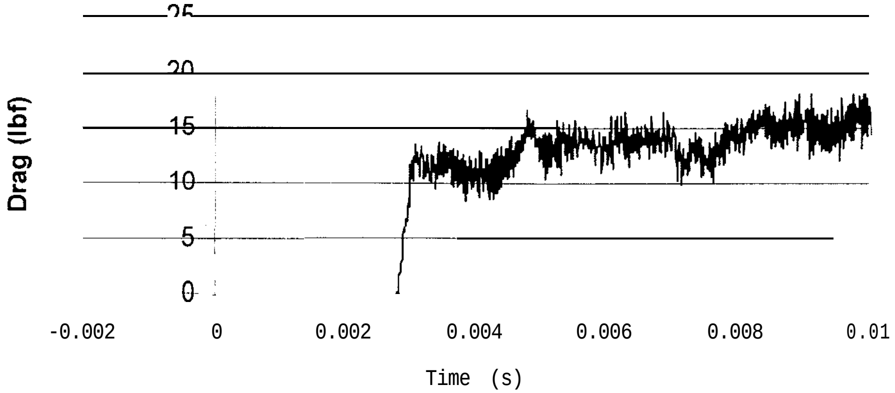


Powered/Unpowered Arc Comparison

Drag Run 26, w/out arc

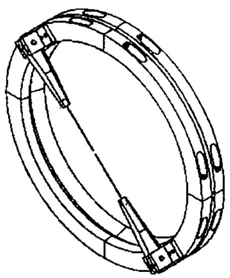


Drag Run 27, w/ arc



@Remarkable change in flow startup drag is clear in first part of trace.

•Reduced drag is seen throughout most of the test time.



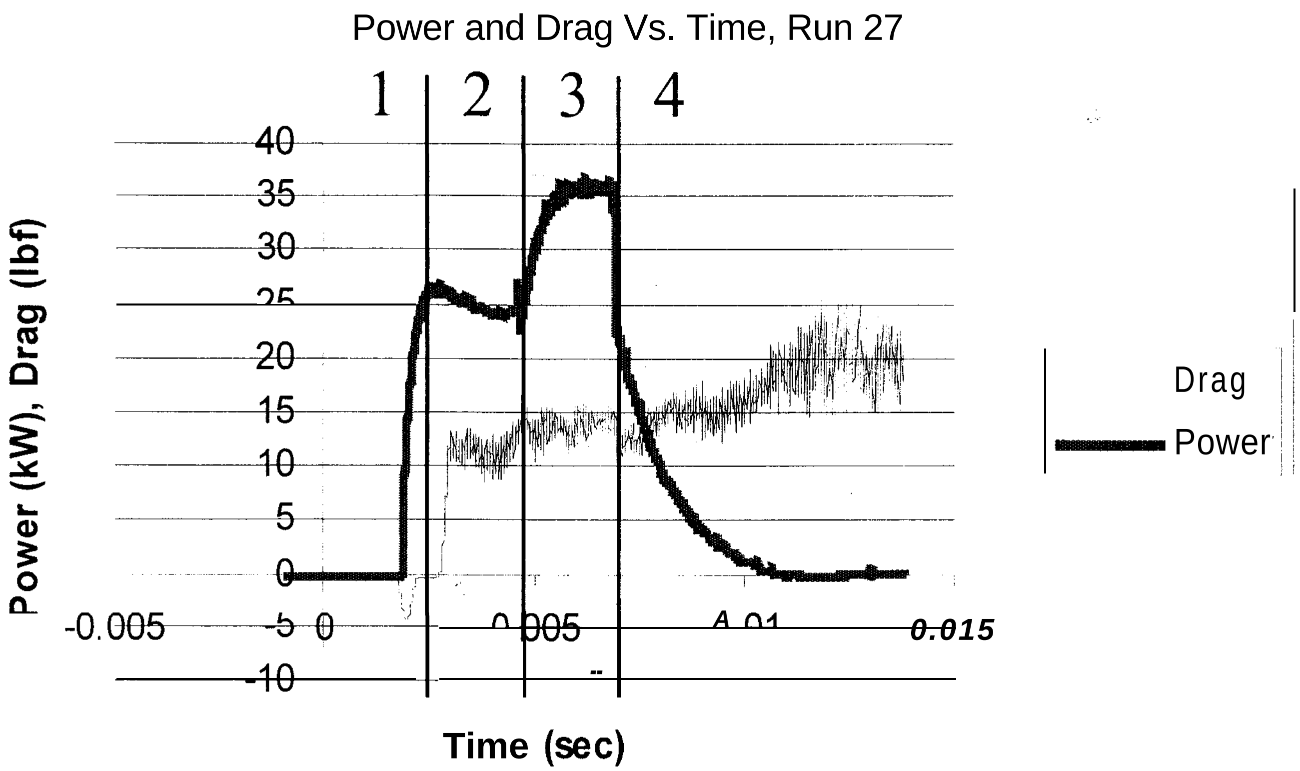
Arc Power Regions

*Region 1, arc startup.

*Region 2, electrodes far apart.

*Region 3, electrodes close together.

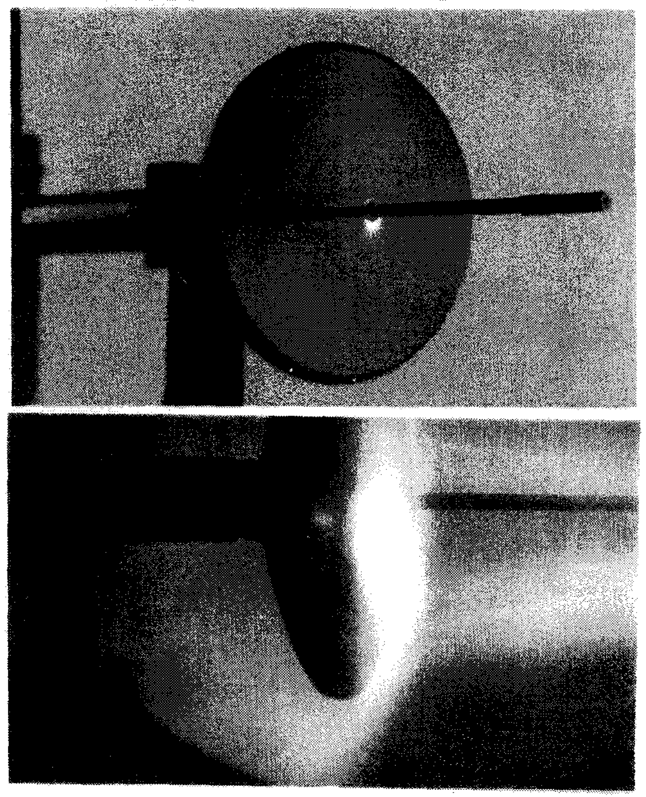
•Region 4, circuit breaker ending test.



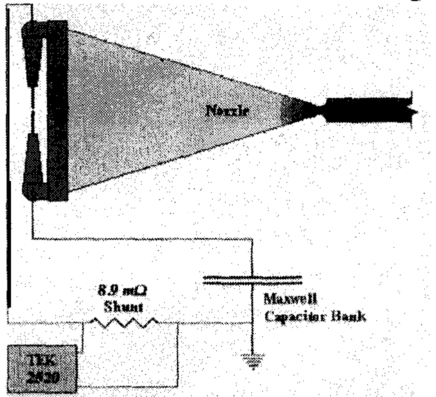
Introduction / Motivation (continued)

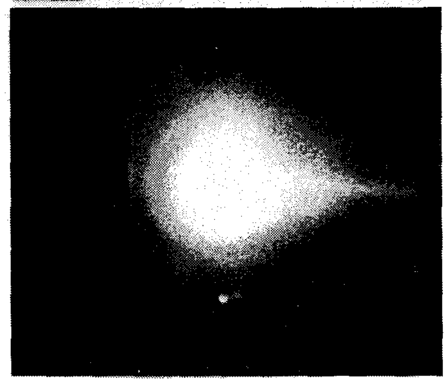
First Attempts to Demonstrate the Directed-Energy "Air Spike"

Electric Plasma Torch



Electric Arc Discharge





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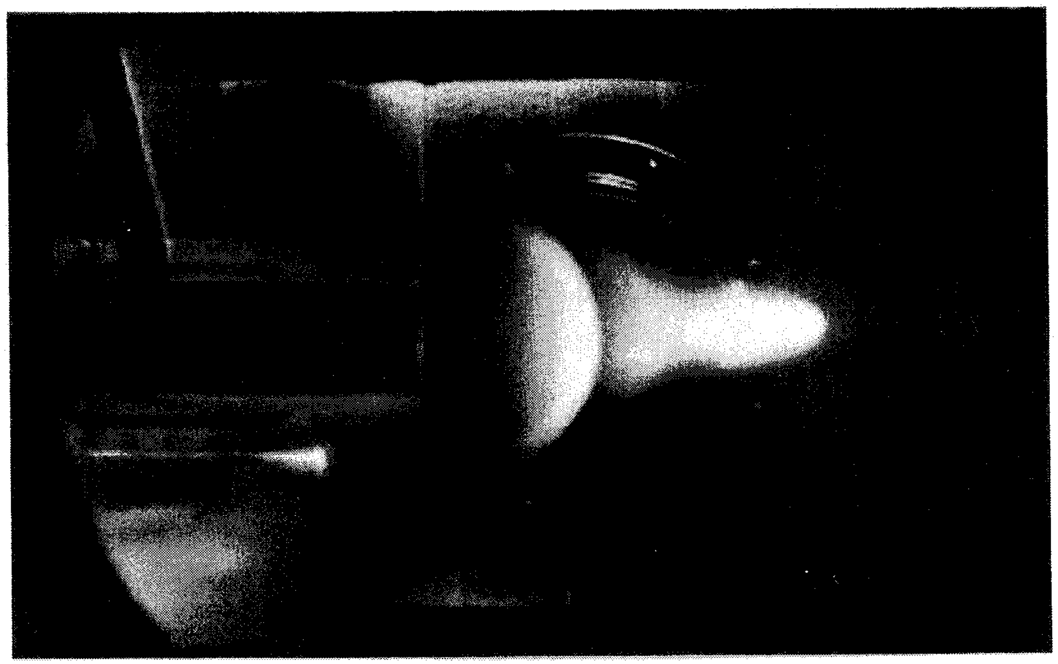
Introduction / Motivation (ended)

The next natural step would be the use of the Laser Radiation to generate the Air Spike, which is the motivation for the present investigation



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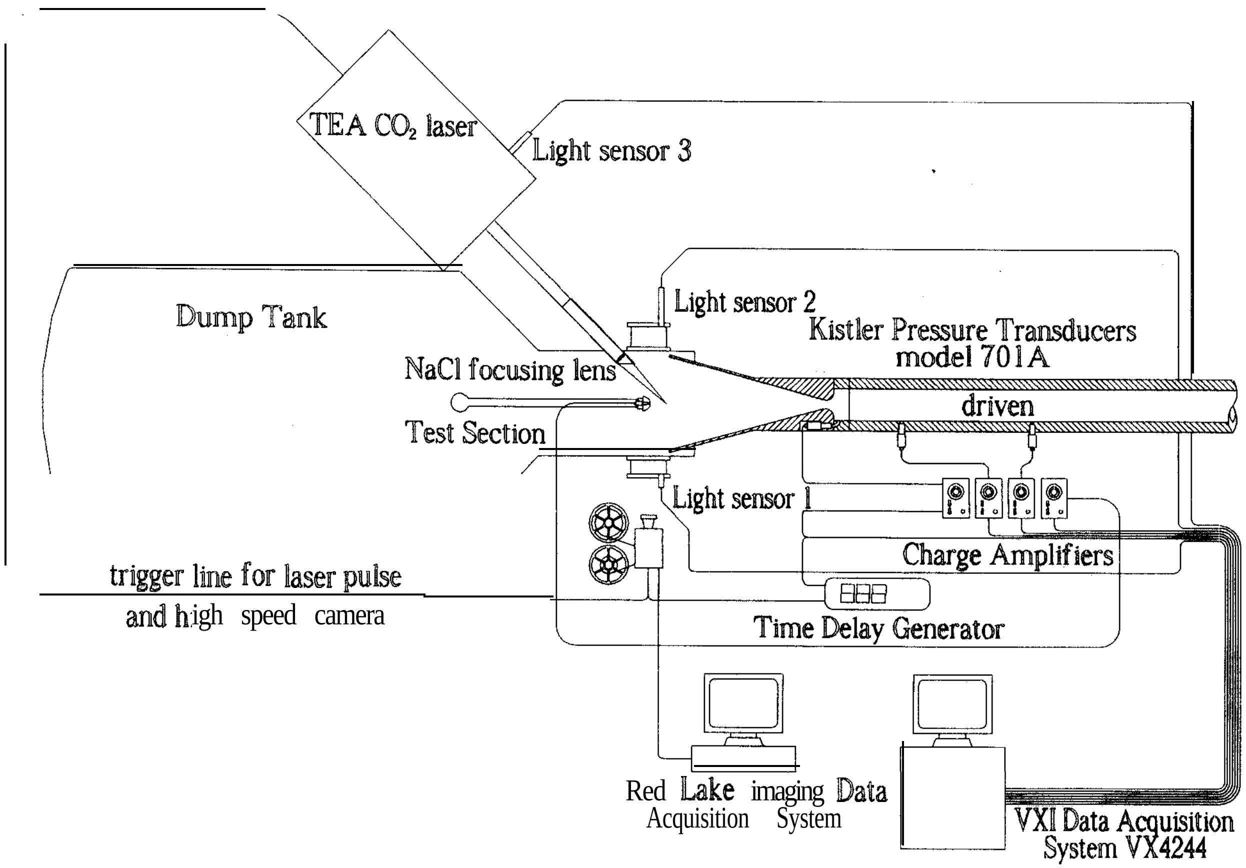
Experimental Apparatus (ended)



Experimental Results

- **Shock Tunnel Test Conditions**

		High Enthalpy	Low Enthalpy
Stagnation Conditions	Pressure (P_0)	120 bar	25 bar
	(Temperature,)	5,000 K	950K
	Enthalpy (h,)	9.0 MJ/kg	1.0 MJ/kg
Free Stream Conditions	Pressure (P_∞)	12.0 mbar	4.0 mbar
	Temperature (T,)	1,000 K	77.0 K
	Density (ρ_∞)	4.0 g/m^3	17g/m^3
	Mach Number (M_∞)	6.2	7.8

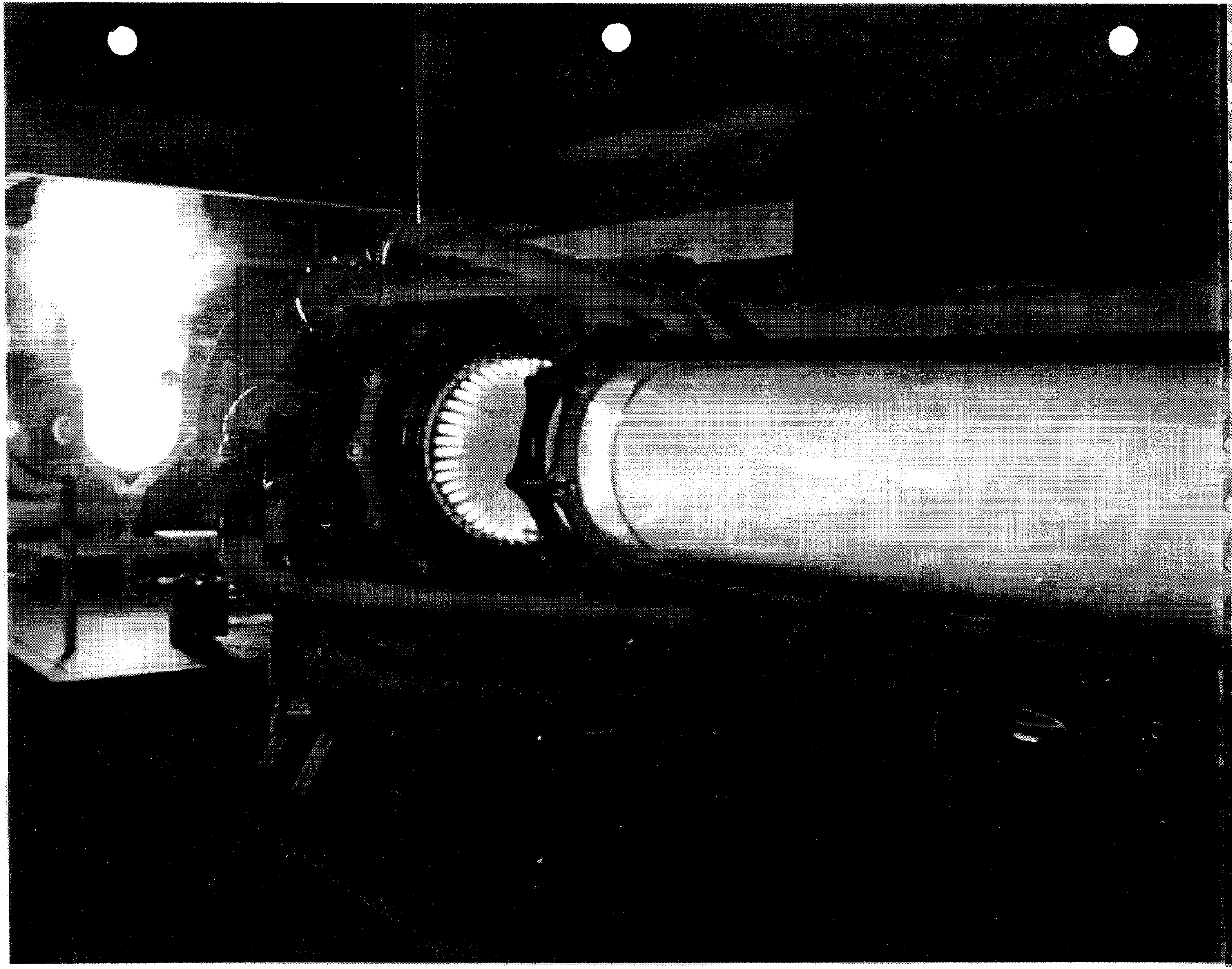
- **CO_2 TEA Laser Conditions**

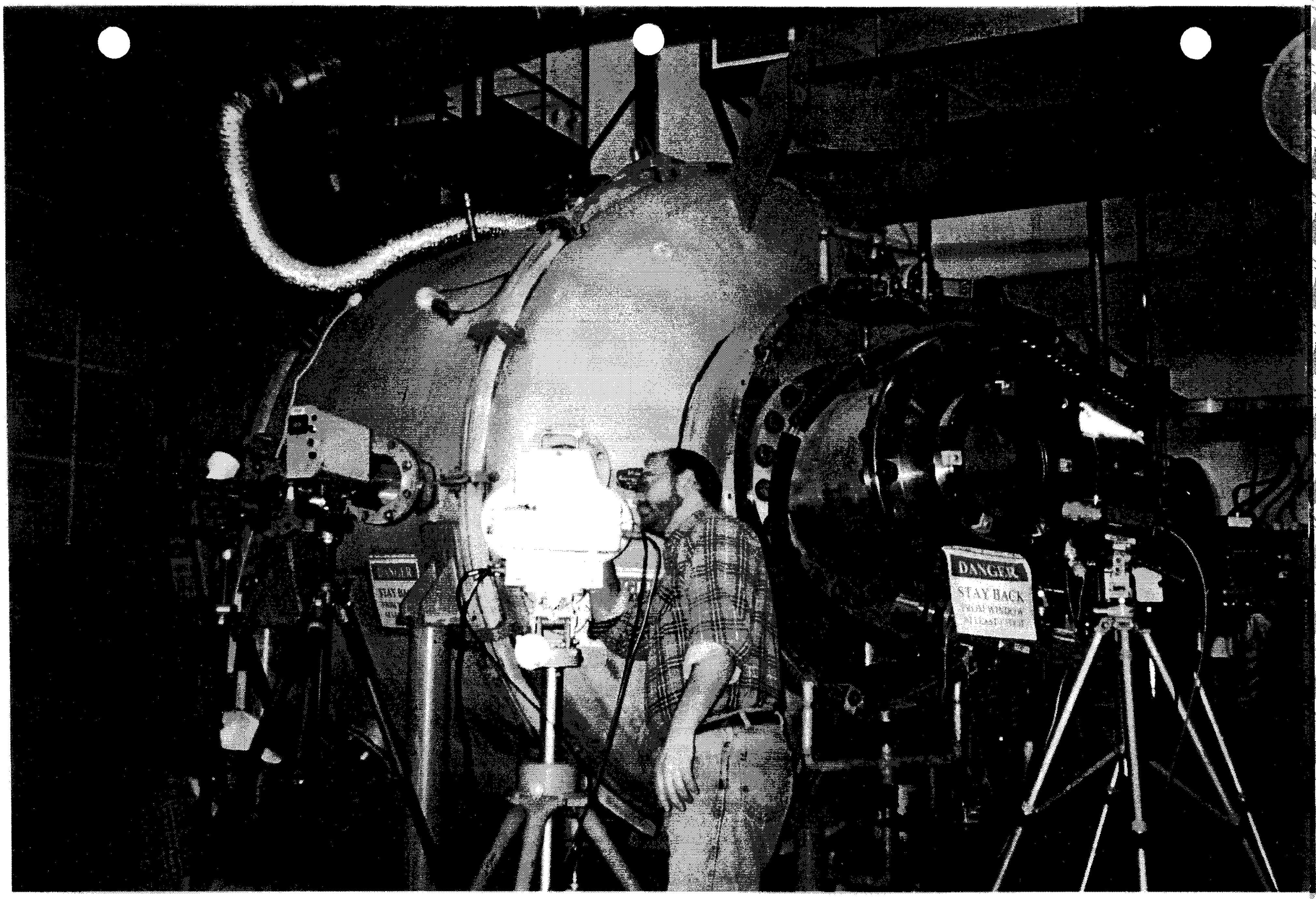
Energy per pulse: 7.5 J
Pulse duration (FWHM): 120 ns

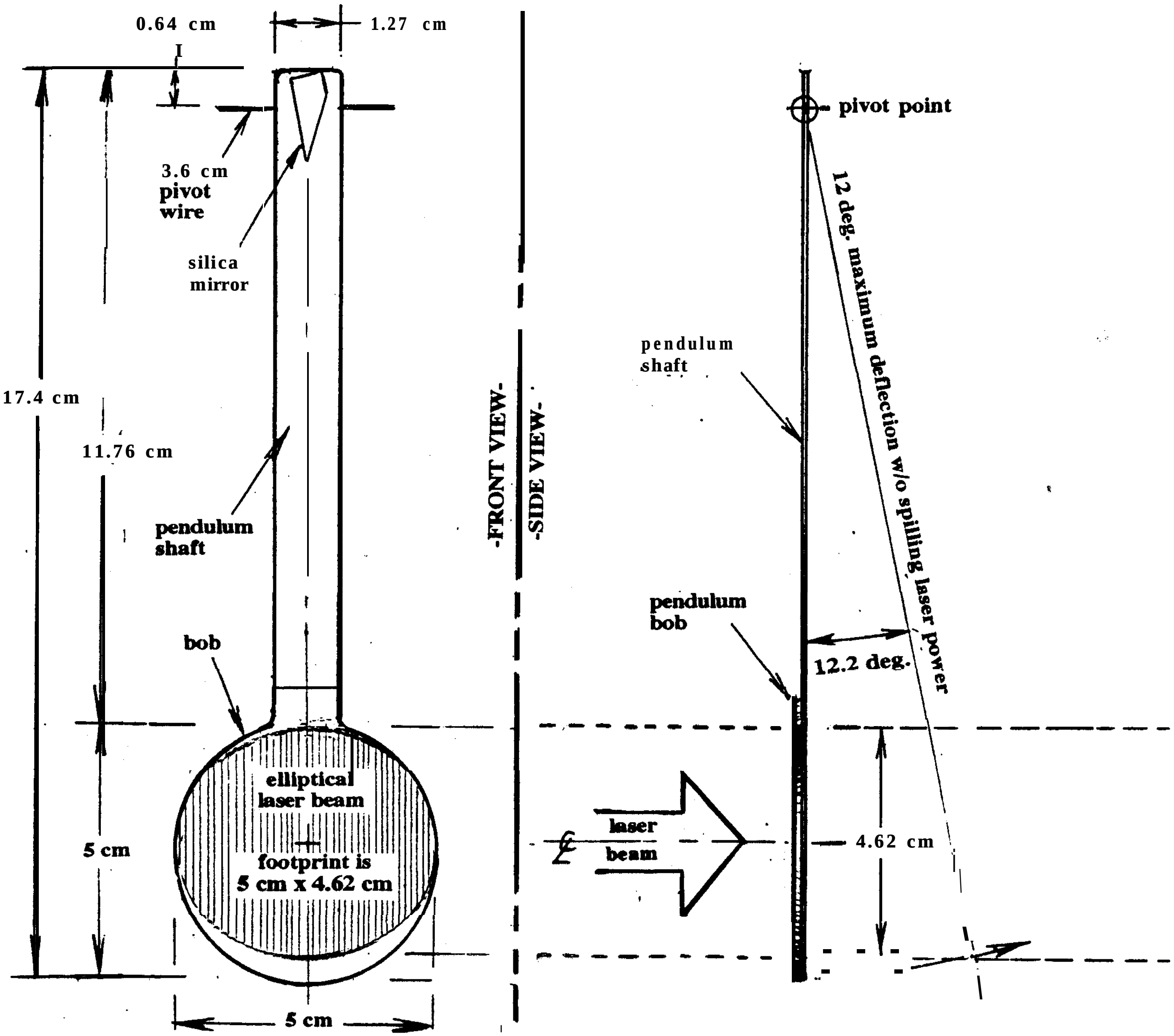
Part II

Laser Sail Experiments
(Sponsored by JPL/ NASA)

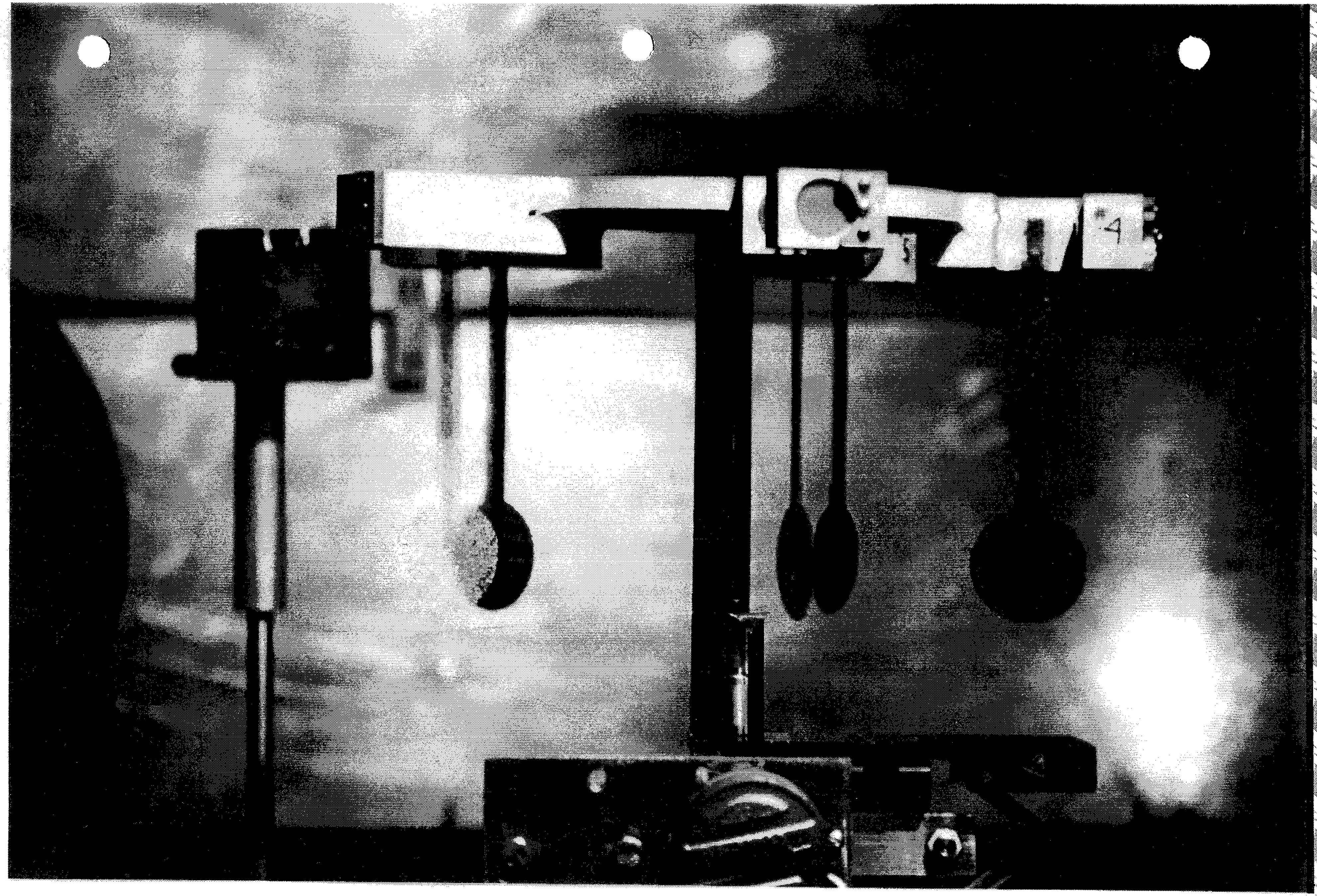
- **5-cm diameter carbon microtruss sails manuf. by ESLI.**
- **Tests used 150-kW LHMEL CO_2 laser at WPAFB.**
- **Review of Dec. '99 pendulum deflection tests.**
- **Latest Dec. '00 vertical wire-guided flight tests.**




DANGER
STAY BACK



0.64 cm
1.27 cm
3.6 cm
pivot
wire
silica
mirror
17.4 cm
11.76 cm
pendulum
shaft
bob
elliptical
laser beam
footprint is
5 cm x 4.62 cm
5 cm
5 cm
-FRONT VIEW-
-SIDE VIEW-
pivot point
12 deg. maximum deflection w/o spilling laser power
pendulum
shaft
pendulum
bob
12.2 deg.
laser
beam
4.62 cm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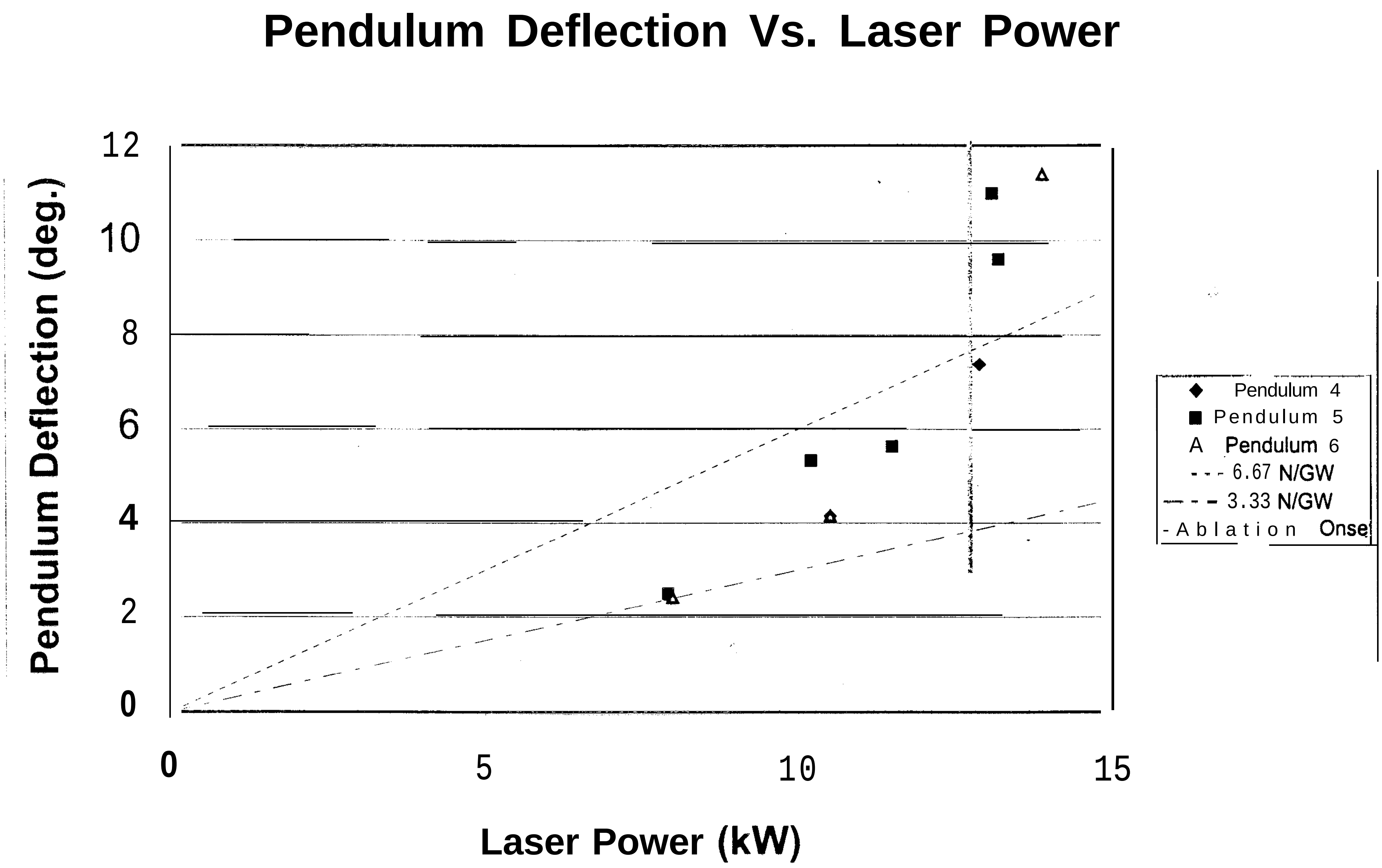


Pendulum Deflection Vs. Laser Power
Pendulum Deflection (deg.)
Laser Power (kW)
0
2
4
6
8
10
12
0
5
10
15
Pendulum 4
Pendulum 5
Pendulum 6
6.67 N/GW
3.33 N/GW
Ablation Onset

Fig 7

Photon Thrust Vs. Laser Power

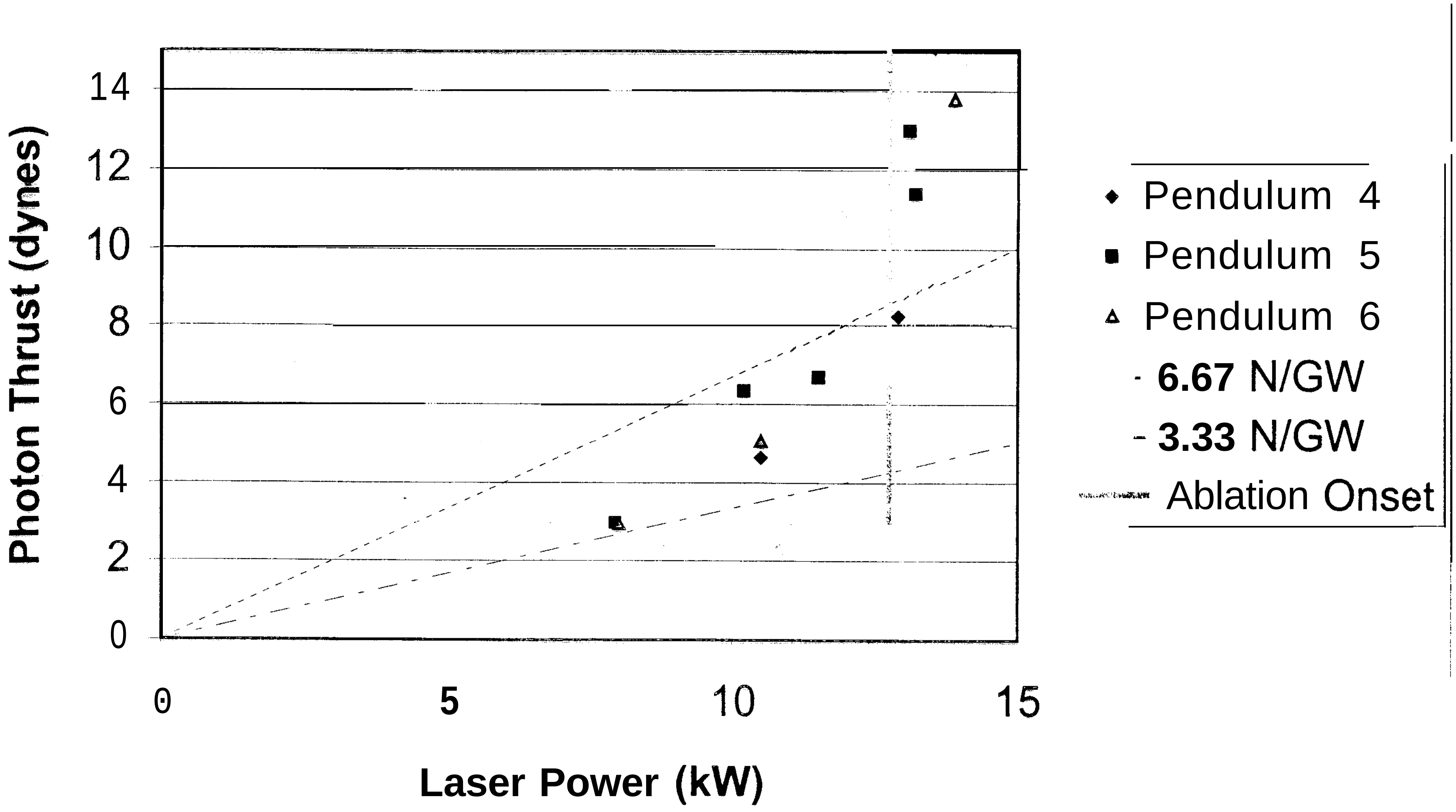


Fig 8

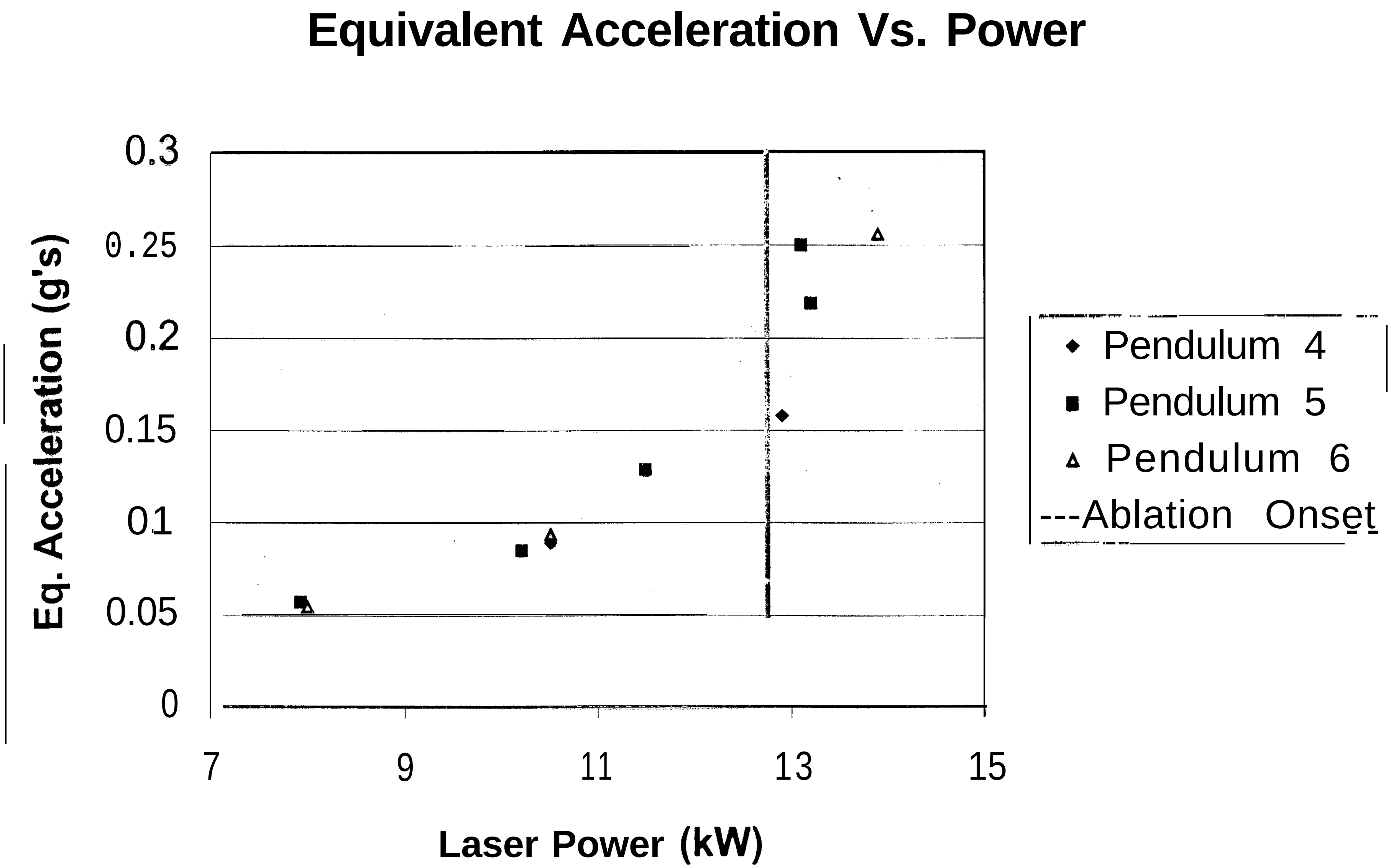

Equivalent Acceleration Vs. Power
Eq. Acceleration (g's)
0.3
0.25
0.2
0.15
01
0.05
0
7
9
11
13
15
Laser Power (kW)
Pendulum 4
Pendulum 5
Pendulum 6
---Ablation Onset

Fig. 1

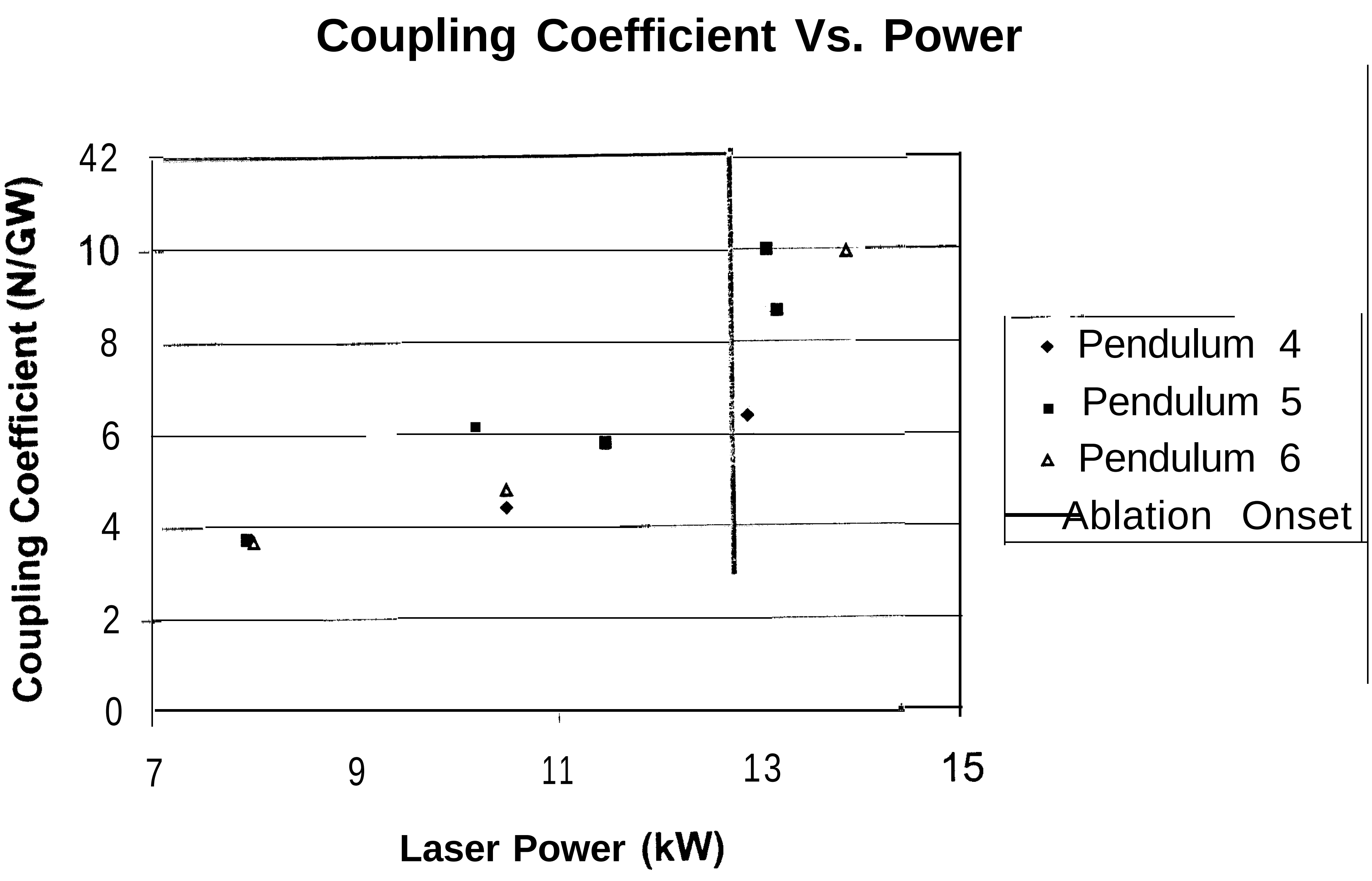
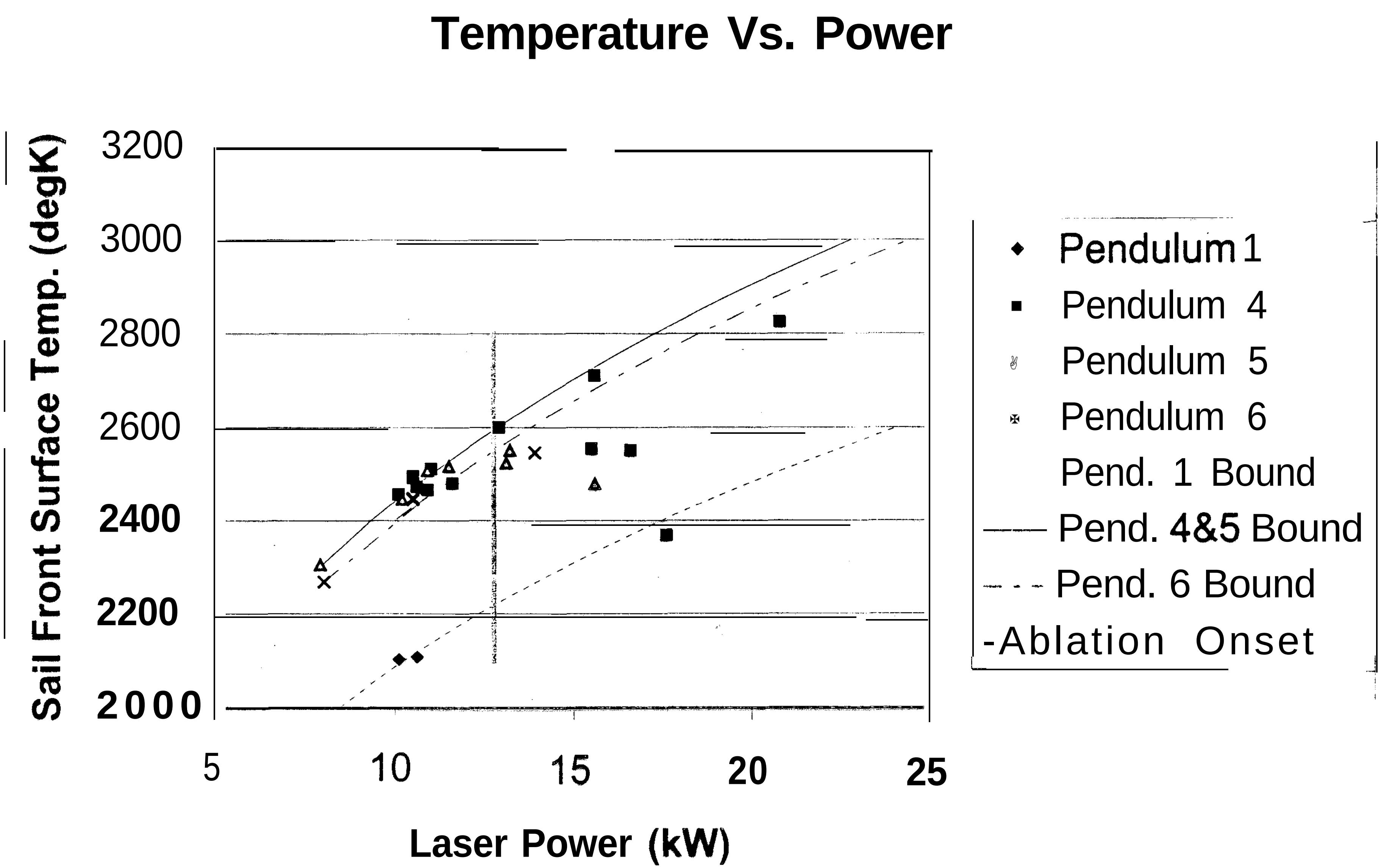

Coupling Coefficient Vs. Power
Coupling Coefficient (N/GW)
42
10
8
6
4
2
0
7
9
11
13
15
Laser Power (kW)
Pendulum 4
Pendulum 5
Pendulum 6
Ablation Onset

Fig 9



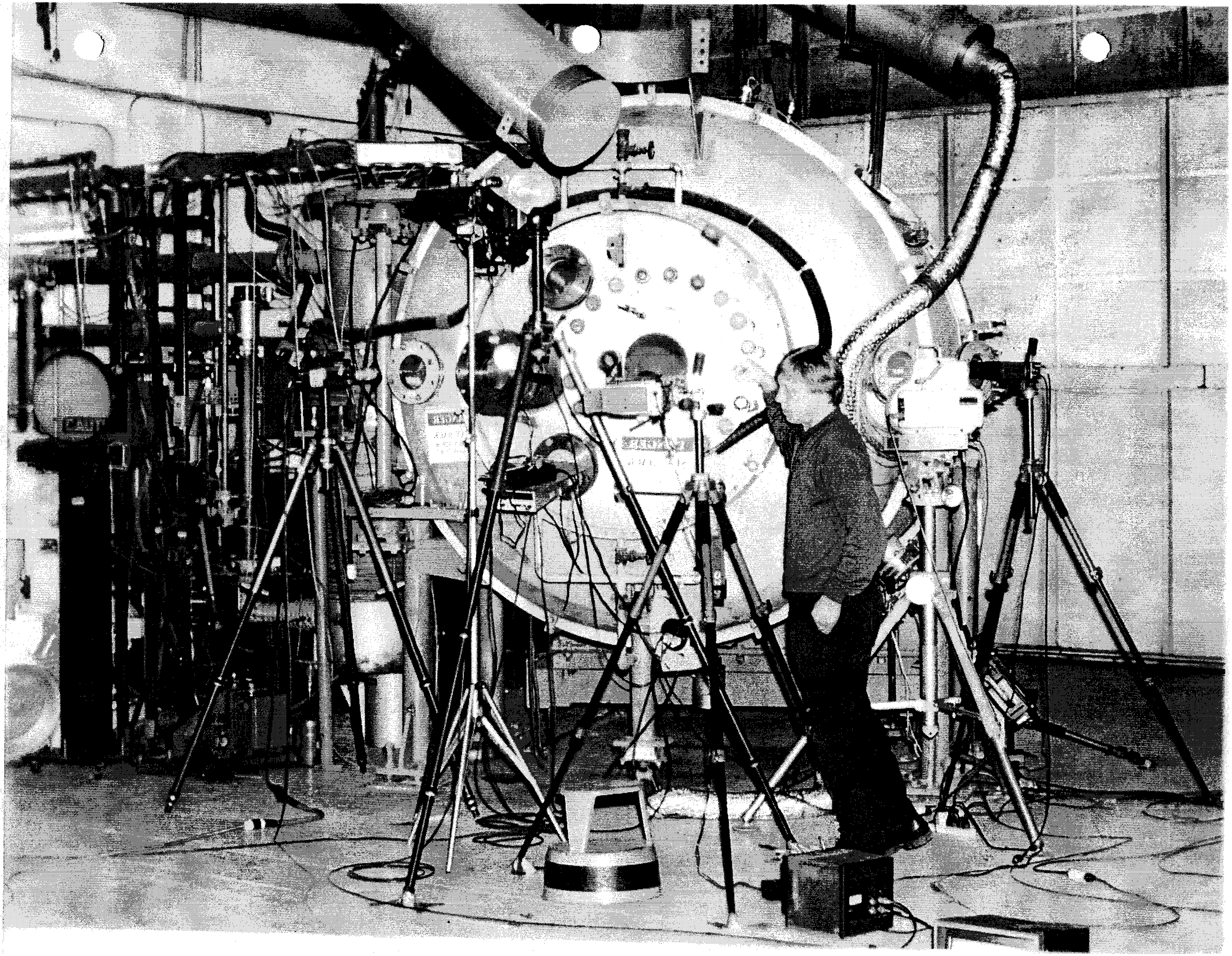
Temperature Vs. Power
Sail Front Surface Temp. (degK)
3200
3000
2800
2600
2400
2200
2000
5
10
15
20
25
Laser Power (kW)
Pendulum 1
Pendulum 4
Pendulum 5
Pendulum 6
Pend. 1 Bound
Pend. 4&5 Bound
Pend. 6 Bound
-Ablation Onset

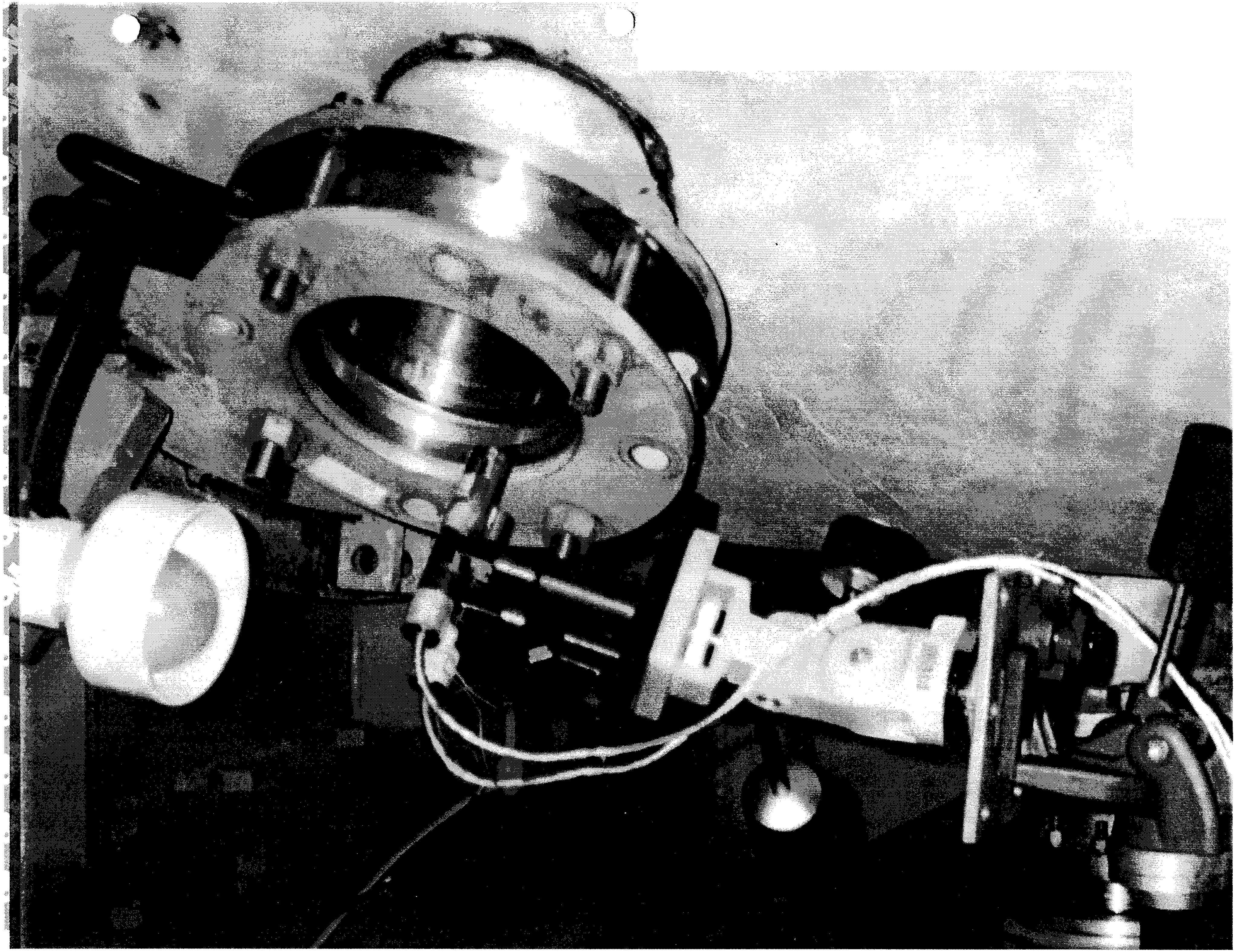
Fig 10

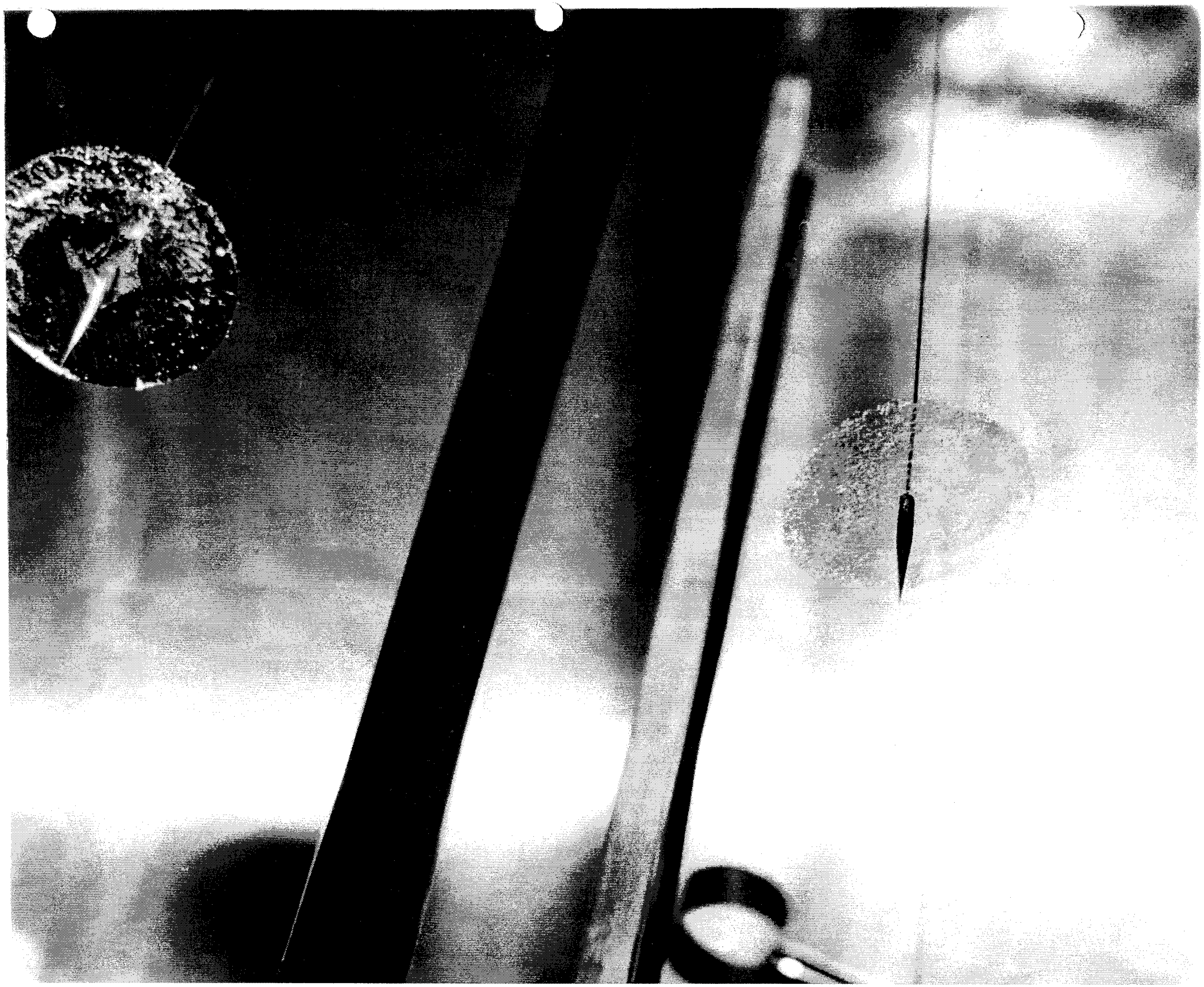
Part II, Cont'd

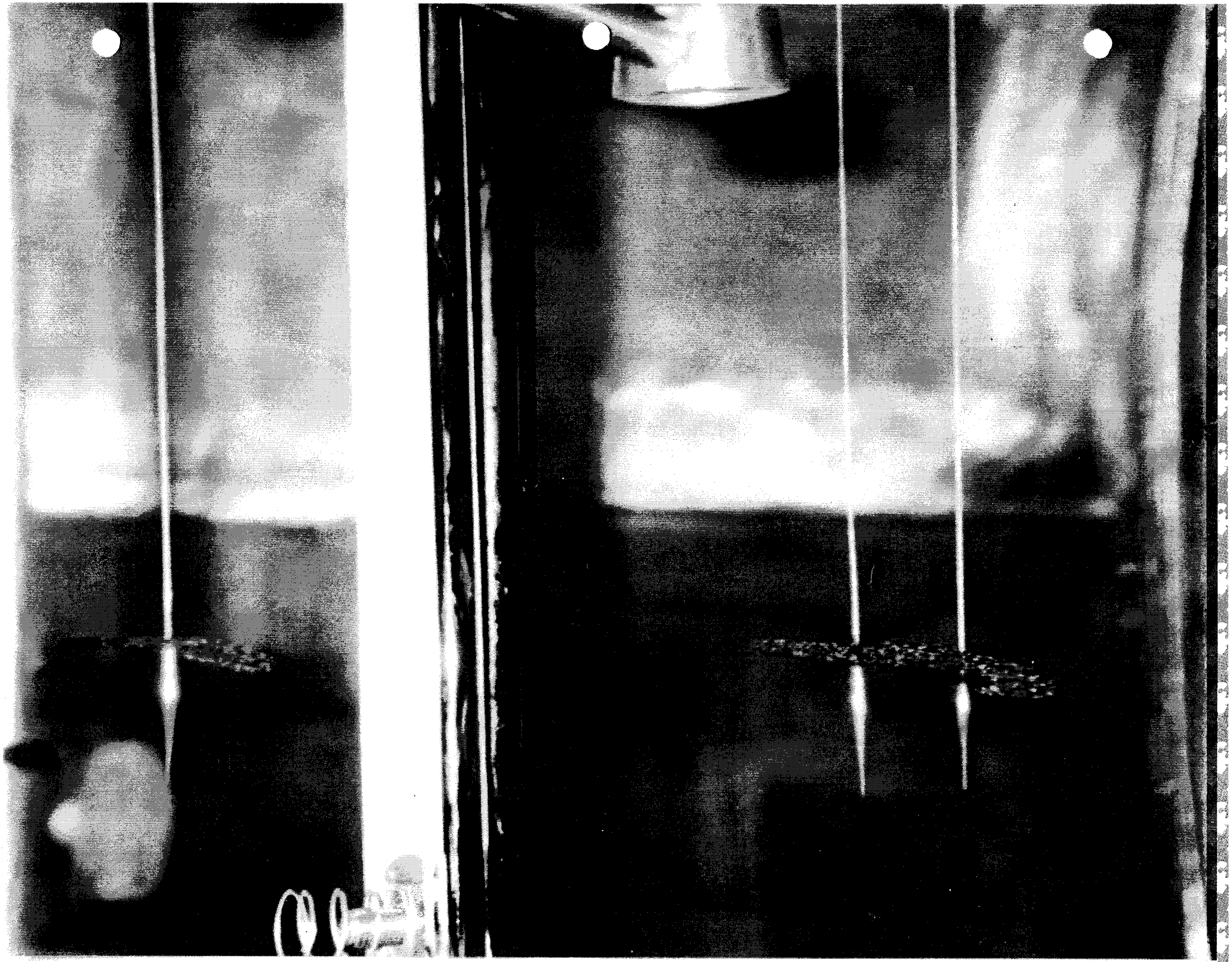
Laser Sail Experiments, Cont'd:

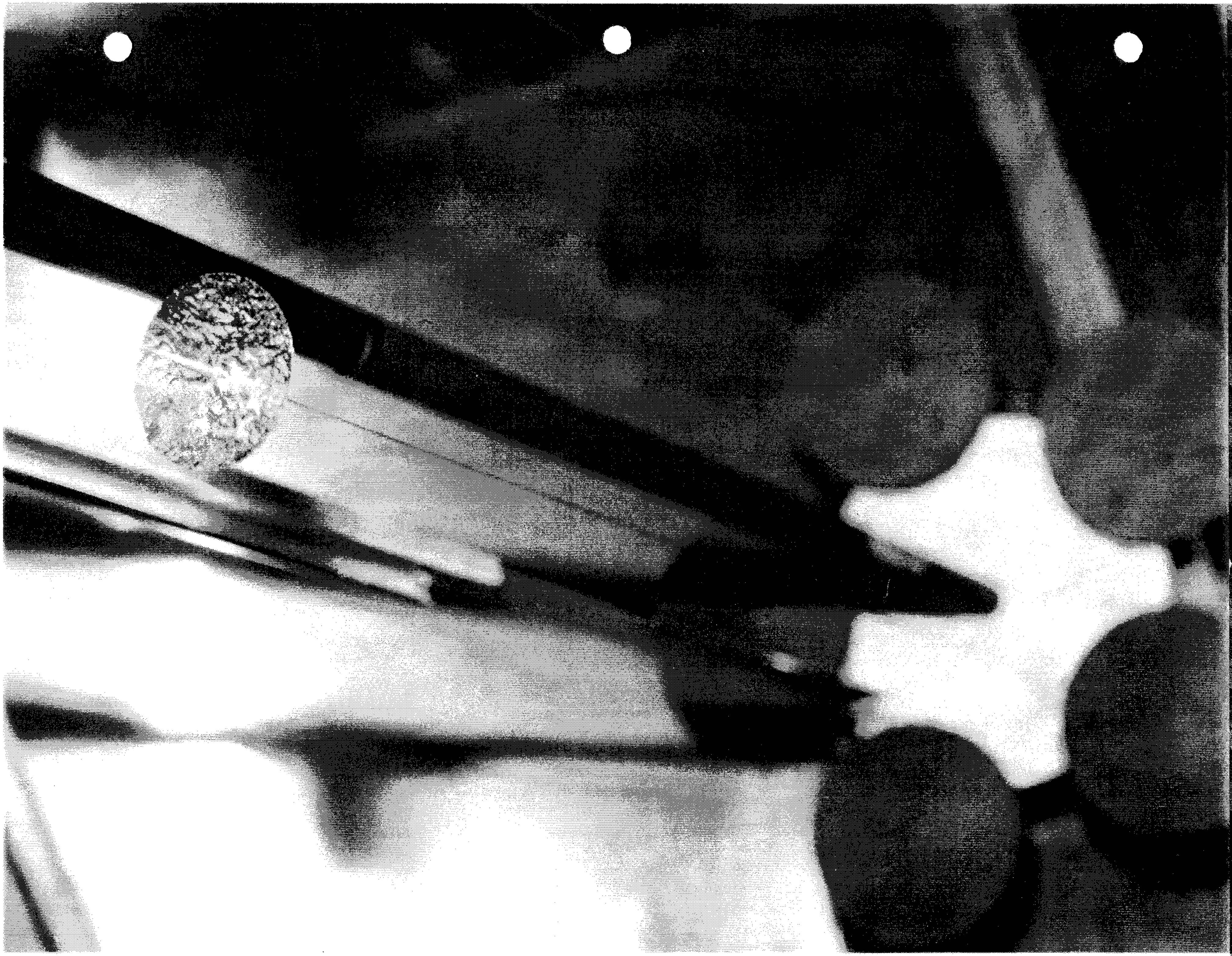
Vertical Wire-Guided Flights @ WPAFB on 4-8 December 2000

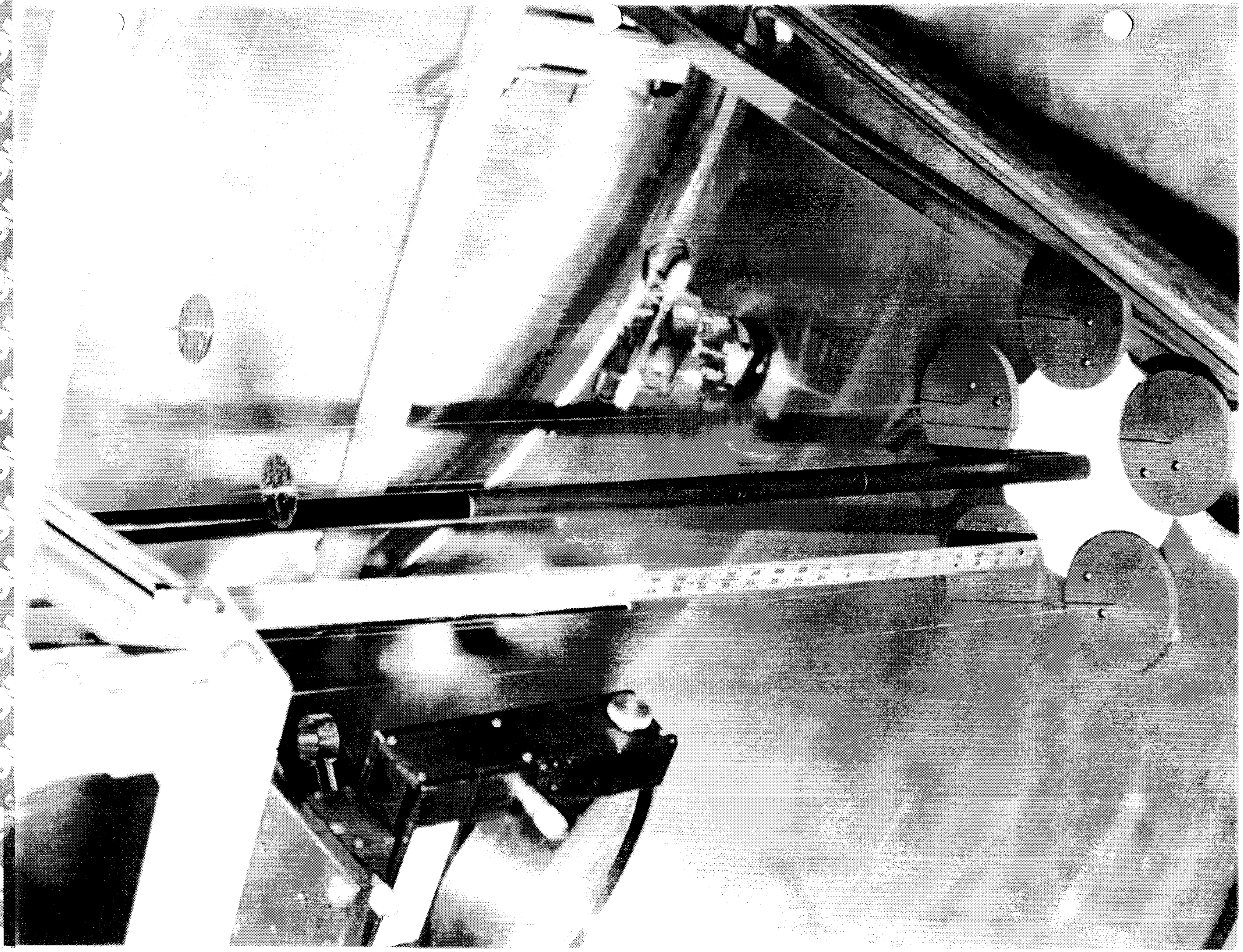












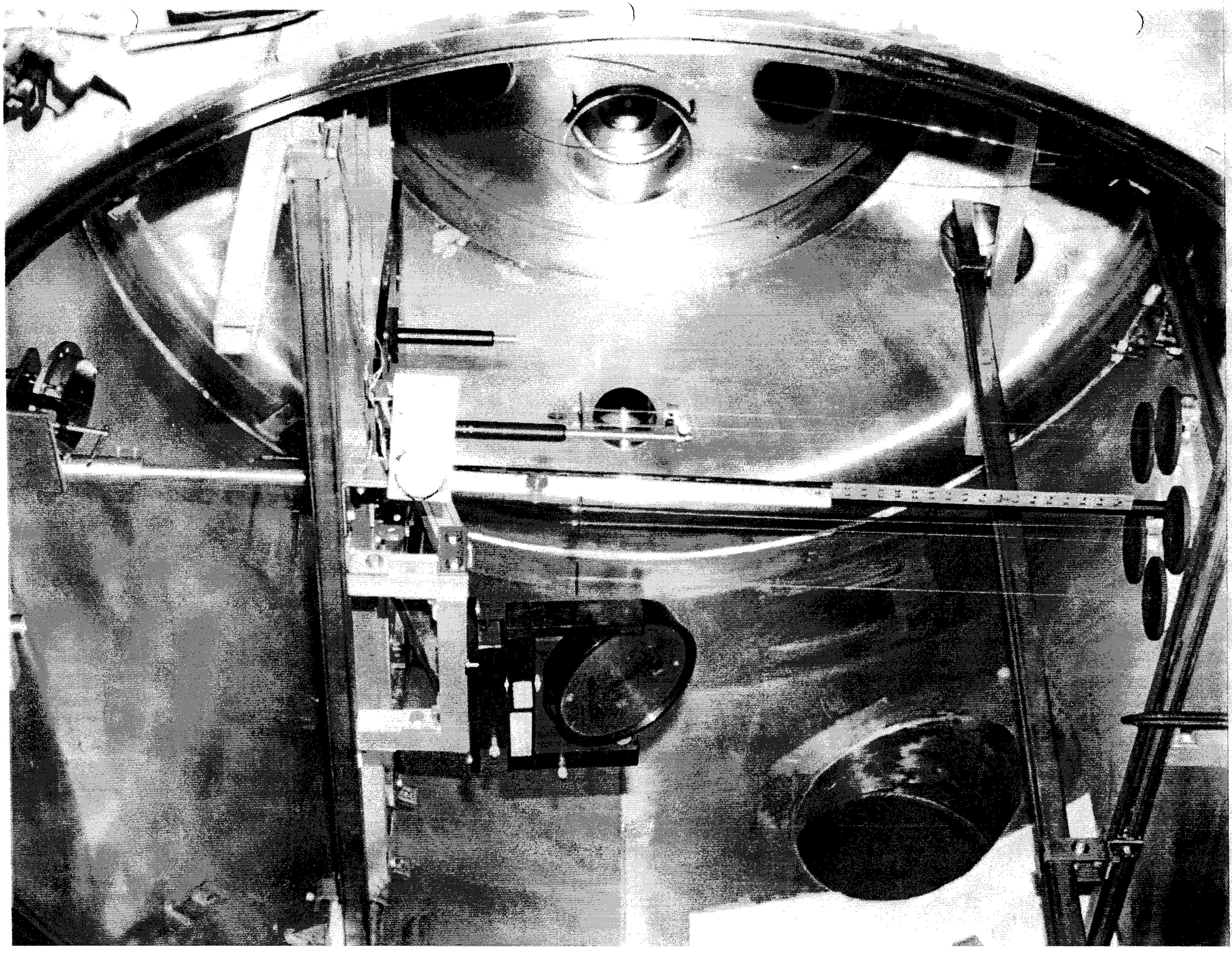


Table 1
Collimated Laser Beam Dimensions Along 90-cm Vertical Guide Wire

Location (cm)	Laser 'Burn' Dimensions (cm x cm)	Laser Beam Area (sq. cm.)	Beam Power Spillage (%)
launch point	5.44 x 5.78	24.7	20.4
40.6 up	5.64 x 5.72	25.3	22.4
81.3 UD	6.20 x 5.82	28.3	30.

Table 2
S-cm Carbon Foil Sail Data (from ESLI, Dec. 2000)
(carbon fiber microtruss + carbon foil + molybdenum reflective coating)

Flight Sail No.		#1	#2	#4
ESLI Reference		PL3-6-1	PL3-6-2	PL3-6-4
Carbon Mass	mg	36.2	34.0	34.8
Mo Thickness	nm	100	200	100
Total Sail Mass	mg	34.3	34.8	32.5
Area1 Mass Density	g/sq.m.	9.4	9.6	8.9

Note. Total sail mass includes mass of grommet and attachment mass penalty.

Table 3
S-cm Carbon Microtruss Sail Data (from ESLI, Nov/Dec 1999)
(carbon fiber microtruss fabric + molybdenum reflective coating)

Sail Specimen Number	Area1 Mass (g/sq.m.)	Total Sail Mass (mg)	Delivery Date
#3	6.3	12.7	Dec. 8, 1999
#8	7.3	14.9	Nov. 24. 1999

Note: Total sail mass includes mass of grommet and attachment mass penalty.

Table 4
LHMEL II Laser Sail Test Summary (Dec. 8, 2000)

Run	Sail No.	Laser Power (kW)	Exposure (seconds)	Vacuum (microTorr)	Optical Pyrometer Readings Silicon (K)	Germanium (K)
1	#4	8.2	0.2	29	1644	1488
2	#4	8.5	0.2	29		1563
3	#4	10.	0.3	29		1701
4	#4	20.	0.4	29		2207
5	#4	30	0.5	29	2853	
6	#4	40	0.2	29	3095	
7	#4	50	0.2	32		
8	#4	50	0.2	32	3250	
9	#4	60	0.2	32	3398	
10	#4	70	0.9	32	3521	- (damaged)
11	#1	8.	0.2	18		1517
12	#1	8	0.2	31		1625
13	#1	8	0.2	31		1728
14	#2	8	0.2	31		
15	#3	8	0.2	30		1682
16	#3	8	0.2	30	1914	1839
17	#3	10	0.2	30	1984	1903
18	#3	20	0.2	30	2643	2316
19	#3	30	0.2	30	2987	
20	#3	40	0.2	30	3229	
21	#3	50	0.2	29	3346	
22	#3	50 ***	1.0	29	3388	
23	#3	50 ***	2.0	29	3271	
24	#8	8	0.2	30	2056	1875
25	#8	8	0.2	30	2109	1937
26	#8	45	1.5	30	3424	
27	#8	50	1.5	30	3490	- (damaged)

Note: All laser power and optical pyrometer data given above is preliminary.

*** = Potential > 1-G photonic propelled light sail flights.

Table 5
Eyelet Mass Penalty for 5-cm Laser Sails

Sail Specimen Number	Area1 Mass (g/sq.m.)	Sail Disc Mass (mg)	Total Mass (mg)	Eyelet Mass (mg)	Eyelet Penalty (%)
#1	9.4	18.45	33.9	15.5	83.7
#2	9.6	18.84	34.6	15.8	83.7
#4	8.9	17.47	32.4	14.9	85.1
#3	6.3	12.37	12.7	0.33	2.7
#8	7.3	14.33	14.9	0.57	4.0

Note: Eyelet mass includes mass penalty for attachment to sail disc.

Part III

Laser Lightcraft Flights at WSMR (sponsored by FINDS)

A new World's altitude record of 233-ft was set on 2 Oct. 2000, using the PLVTS laser at the High Energy Laser Systems Test Facility, at White Sands Missile Range.

(Show video of record flights.)

The flights required NORAD clearance, since they were conducted without a laser 'beam-stop,' as was used in all previous tests.

Flights were carried out with the laser Lightcraft model #200-5/6, with several design improvements.

The 50-gram aluminum Lightcraft vehicles sustained no damage in 13-second long flights, and will fly again.

This flight research was conducted by Lightcraft Technologies, Inc.

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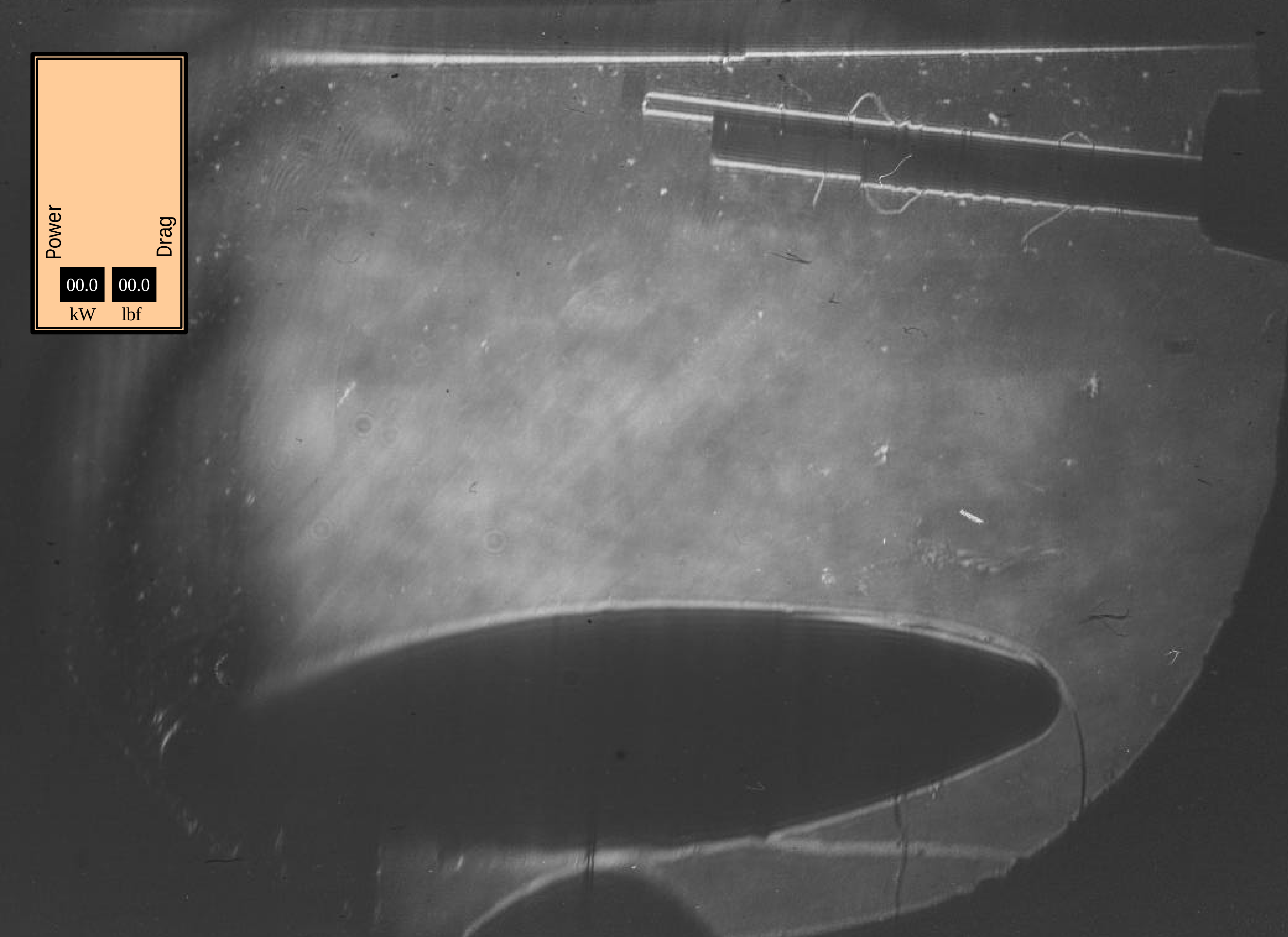
DEAS Run 27

22 MAR 2001

5 Batteries

28 frames @ 4.5 kHz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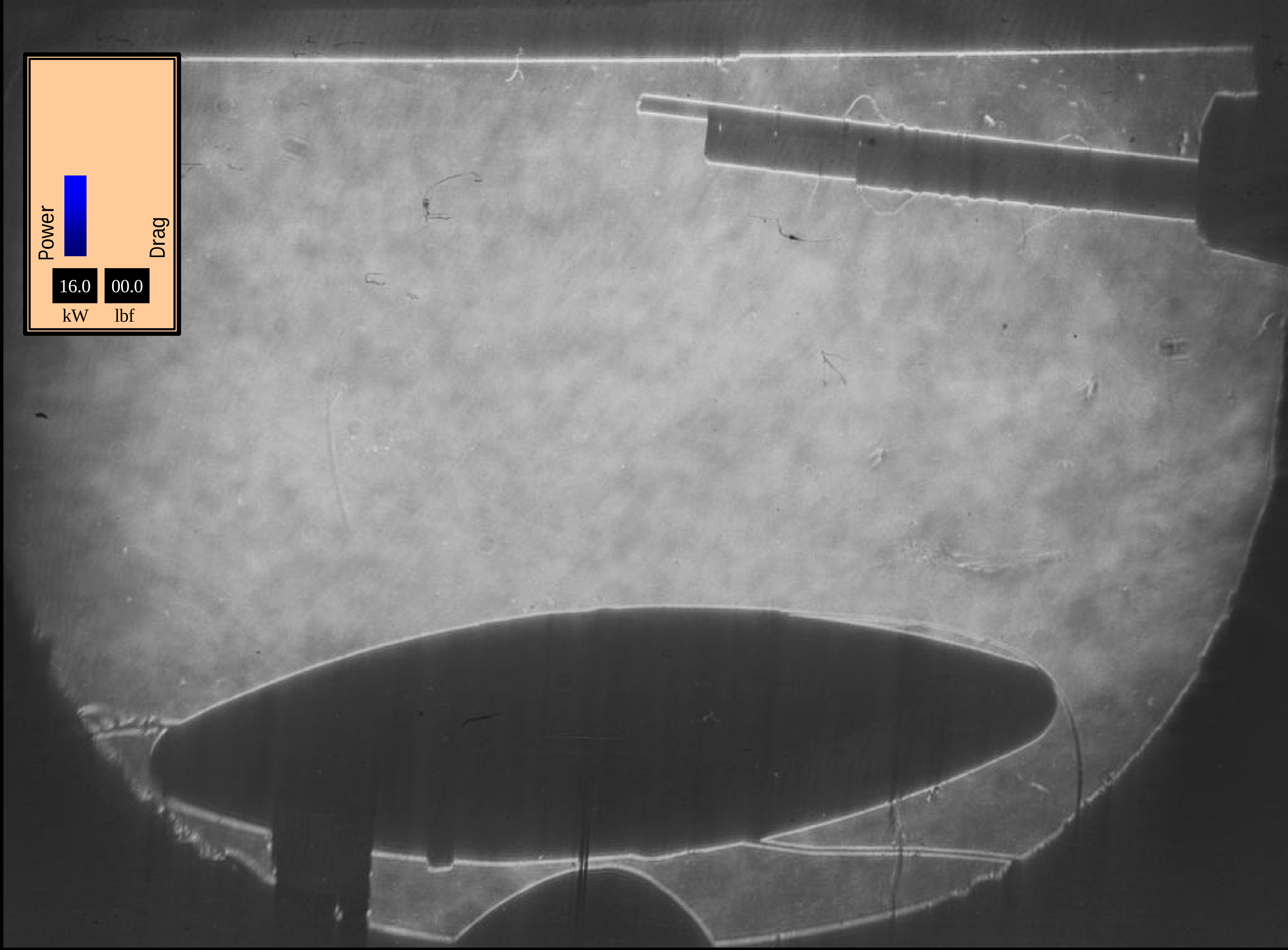

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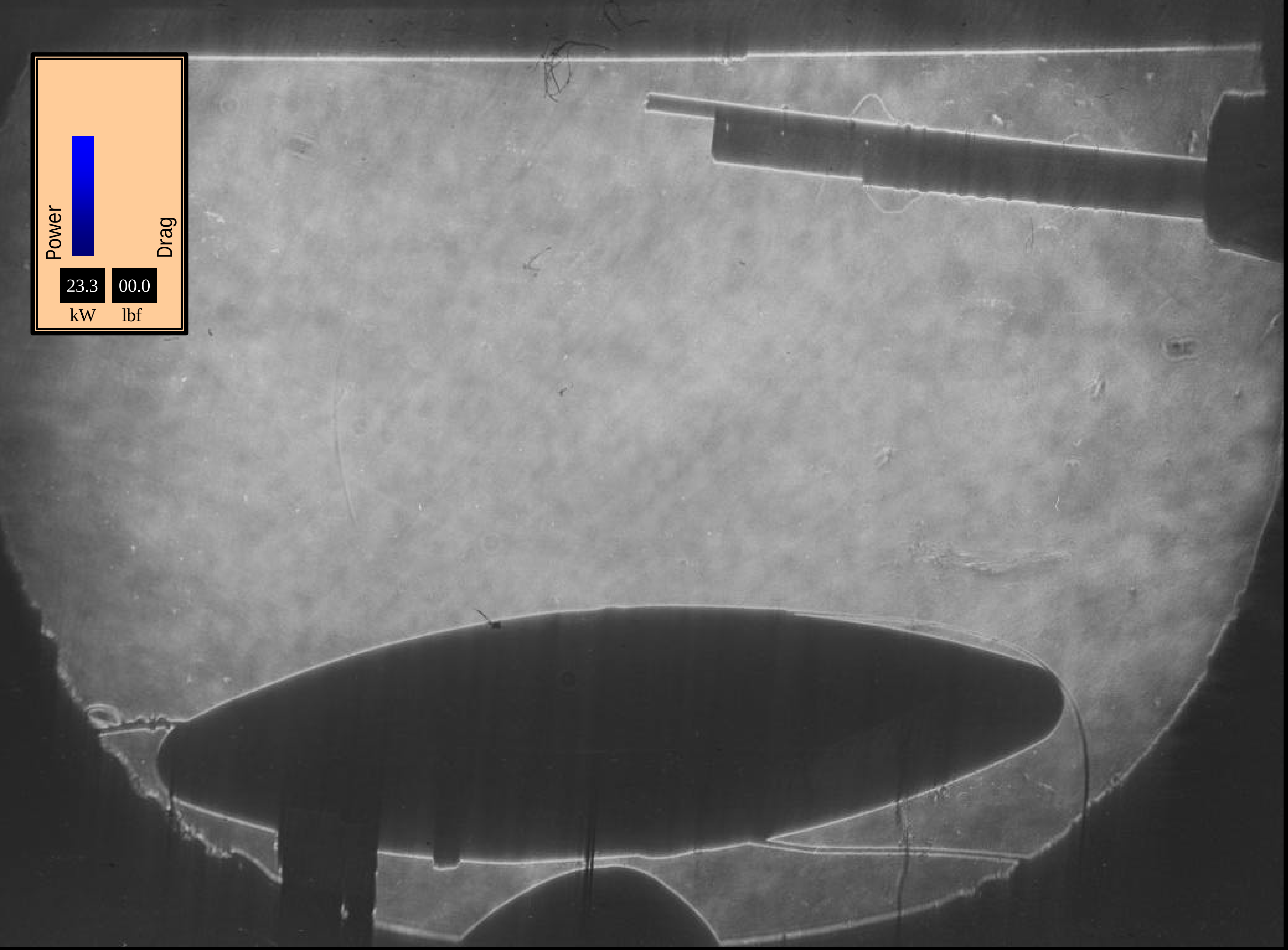
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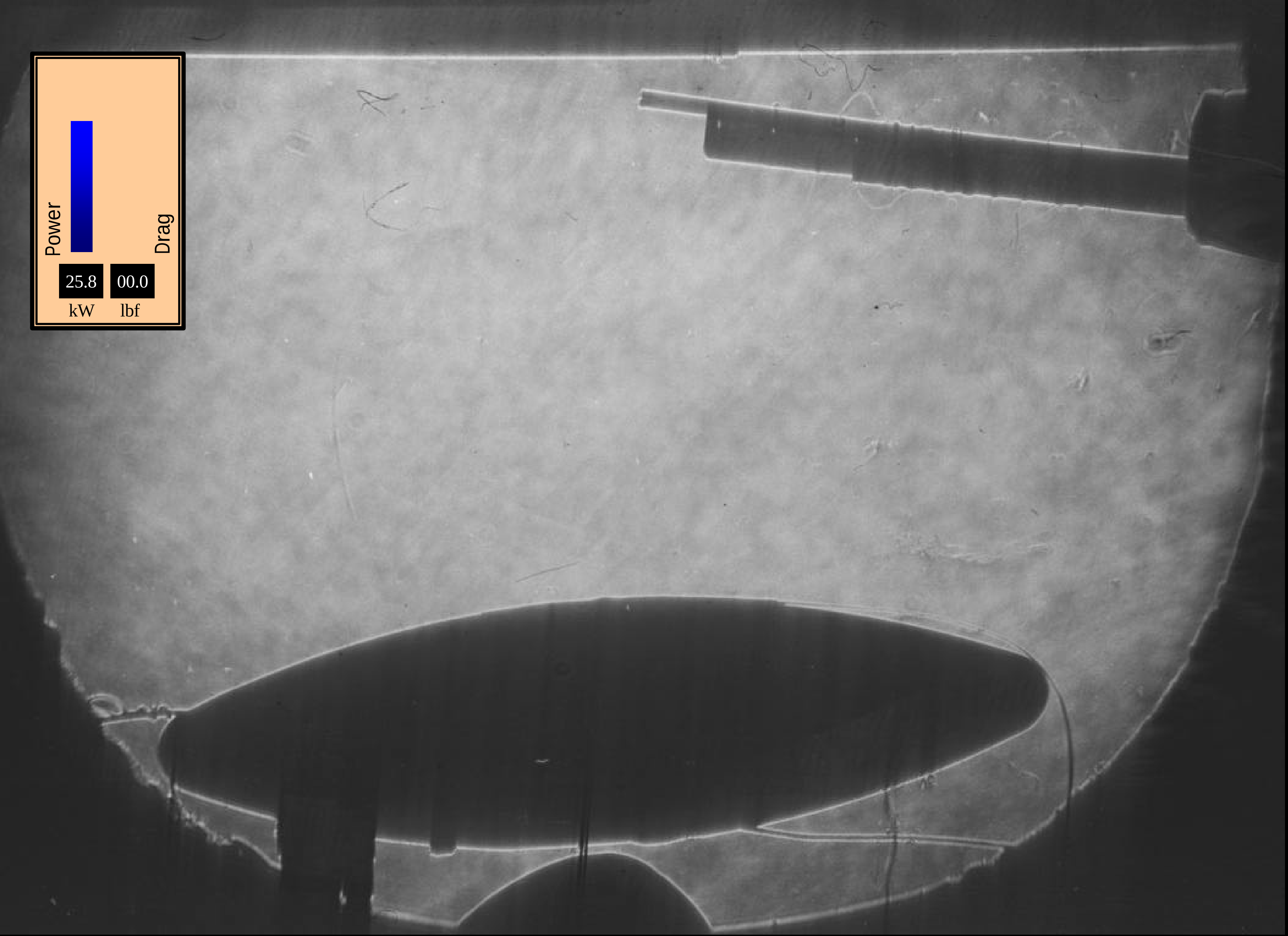
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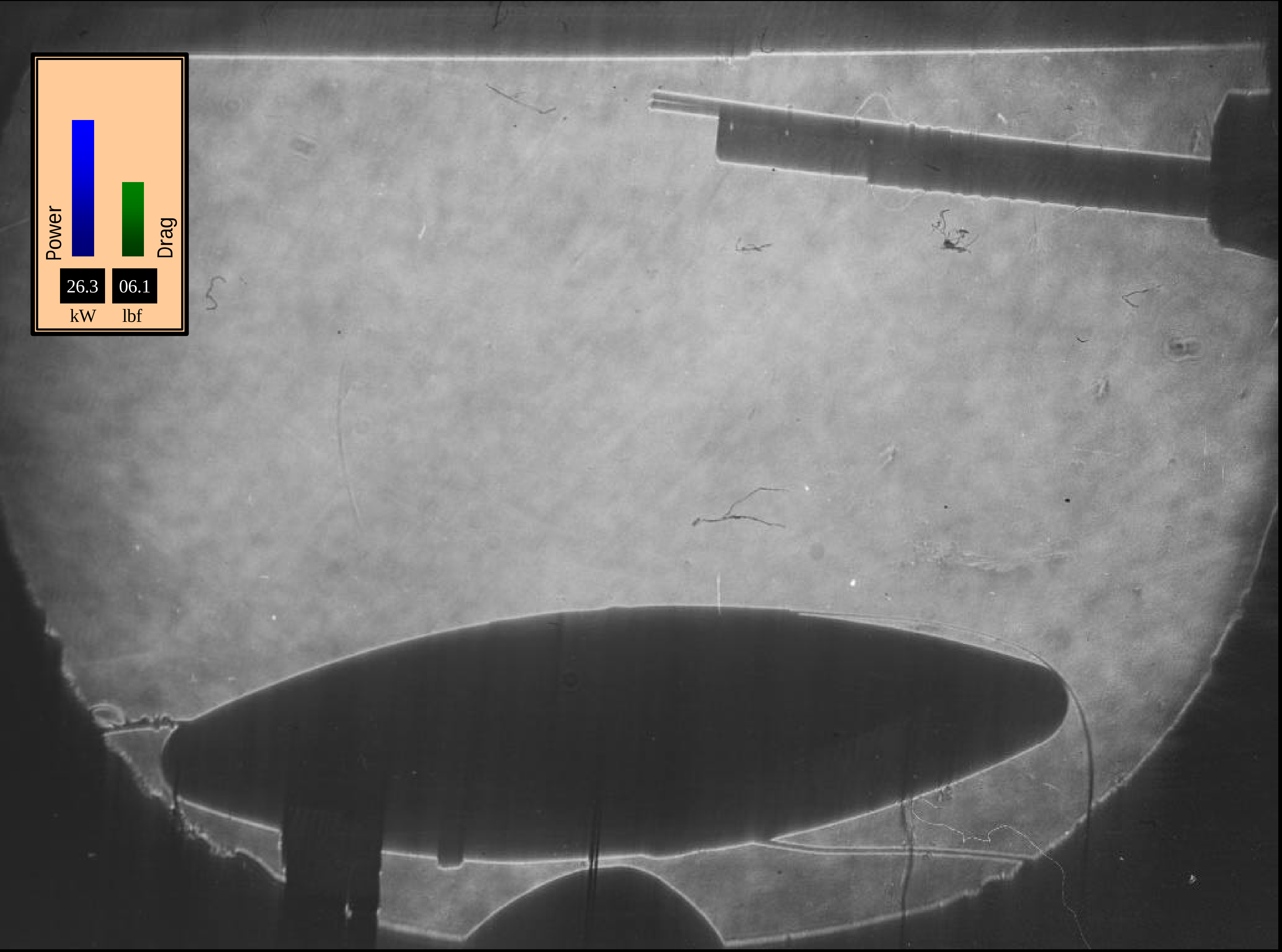
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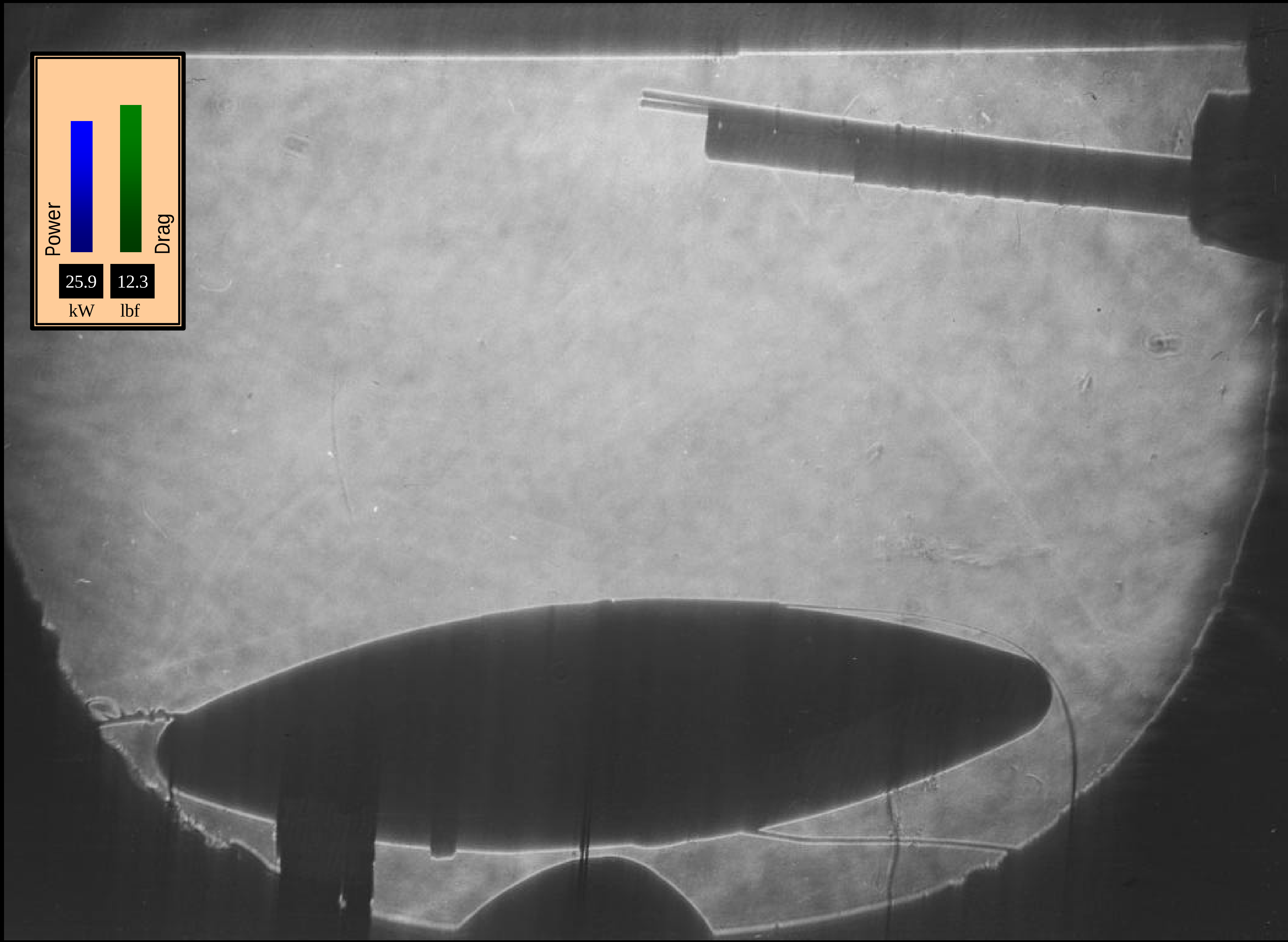
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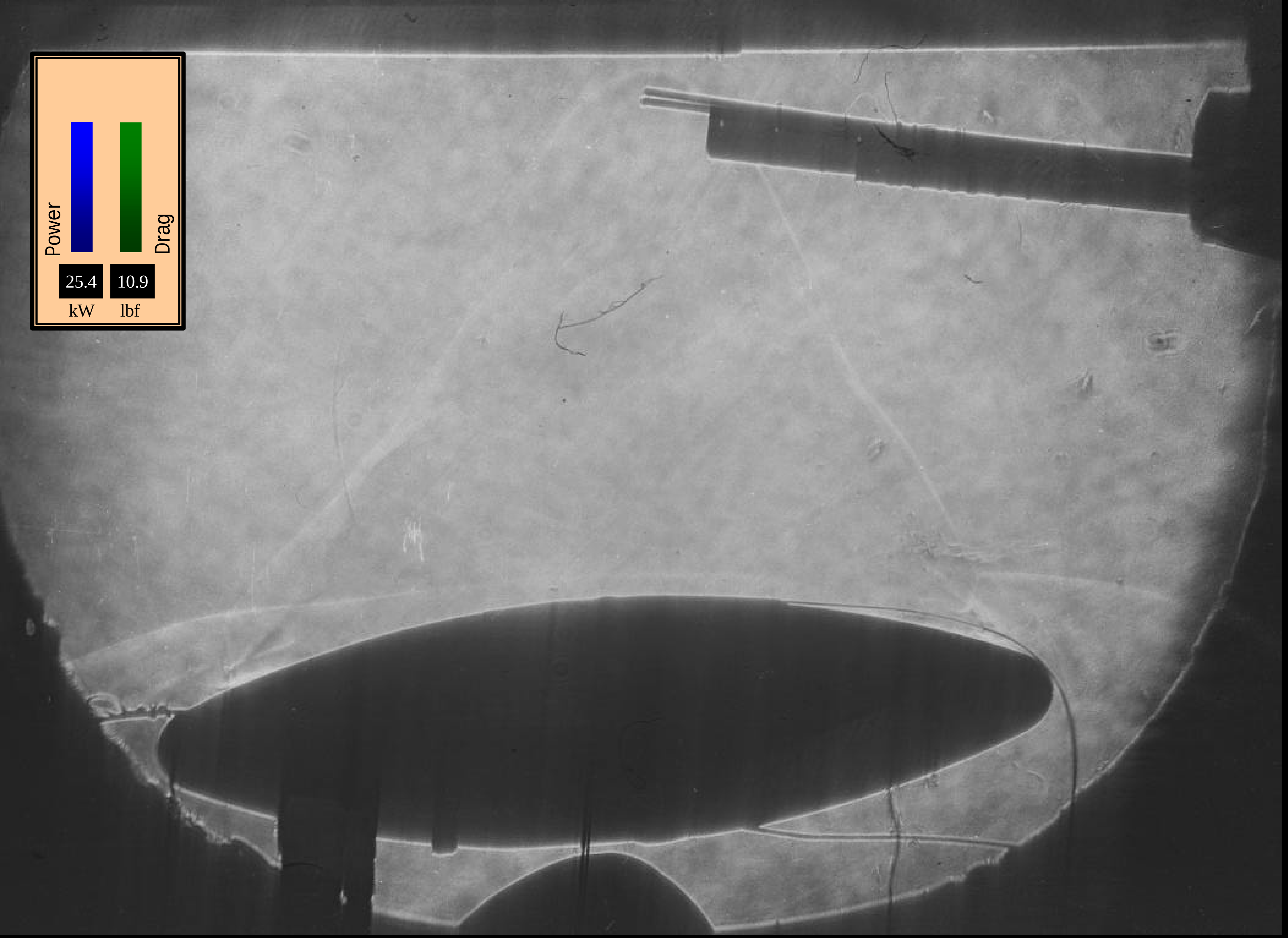

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kW
lbf


Power
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kW
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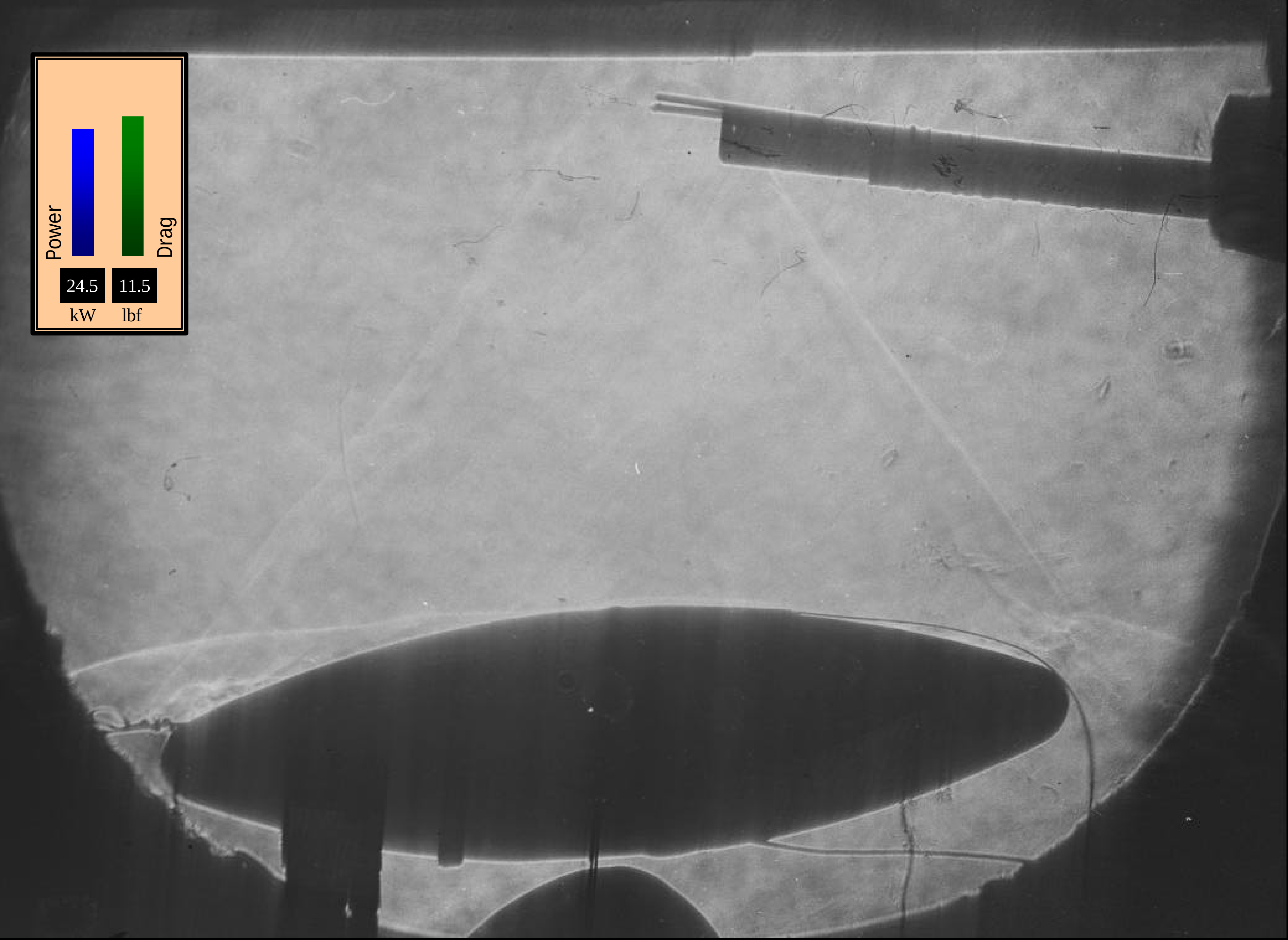
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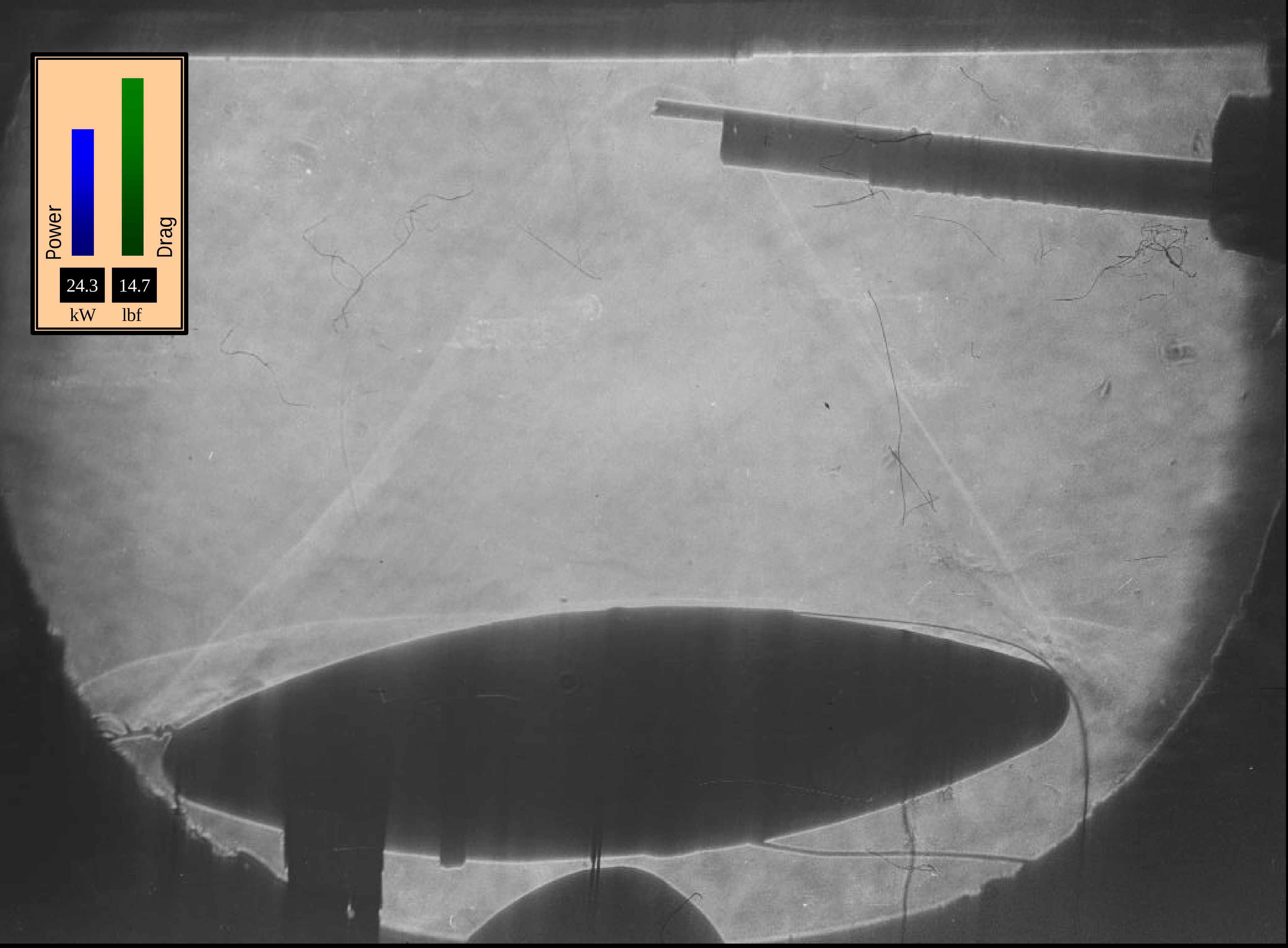

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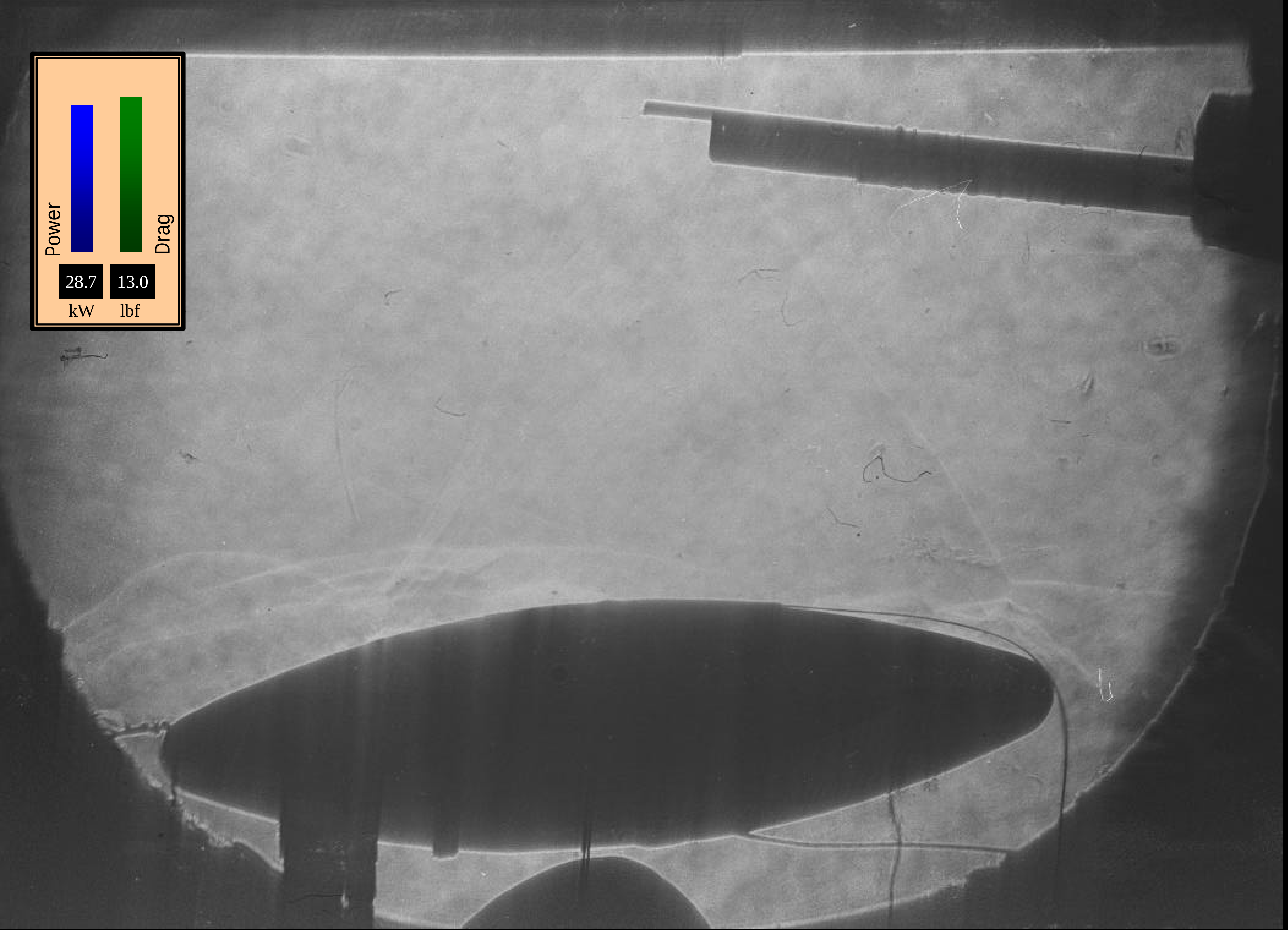
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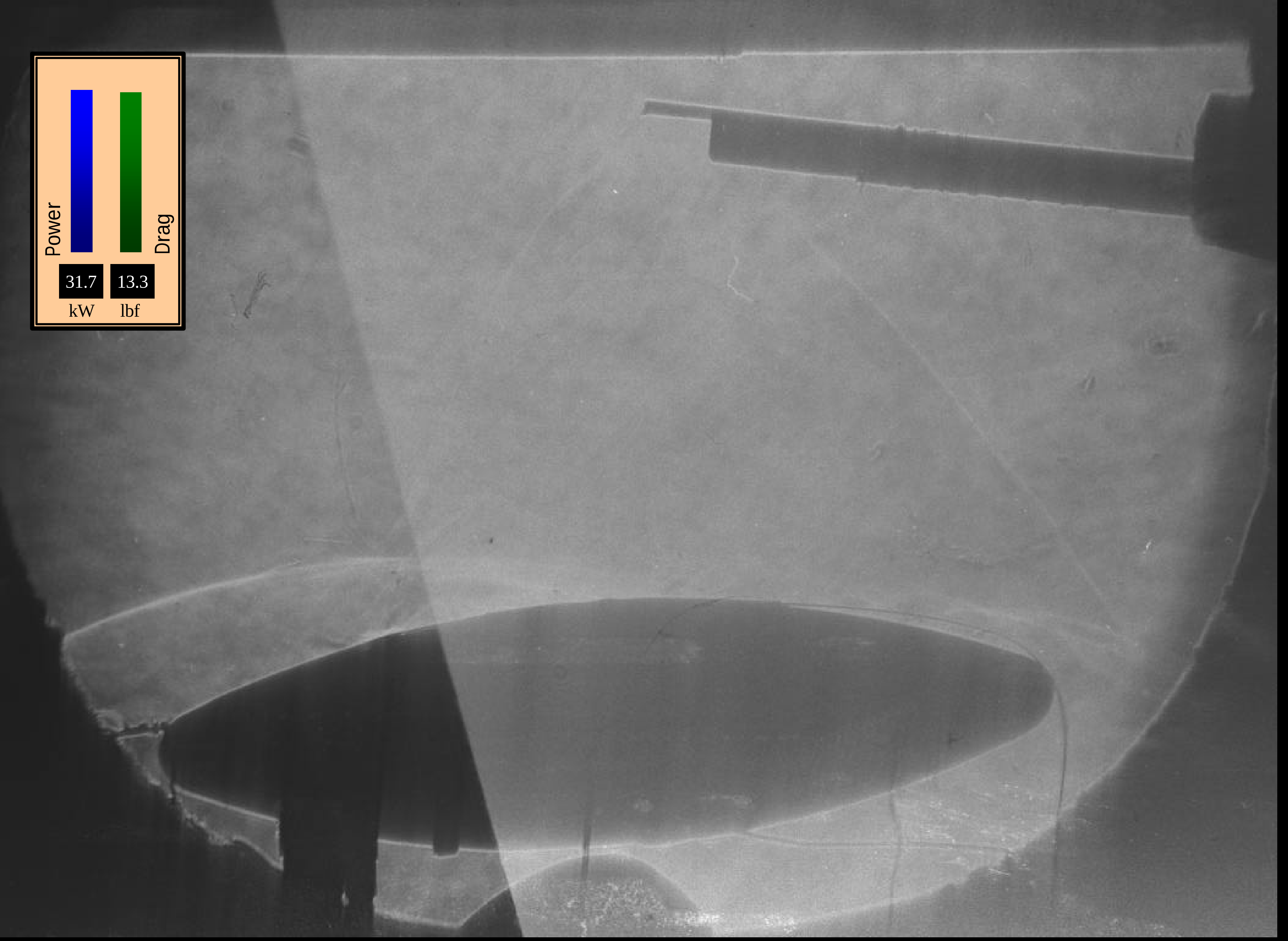
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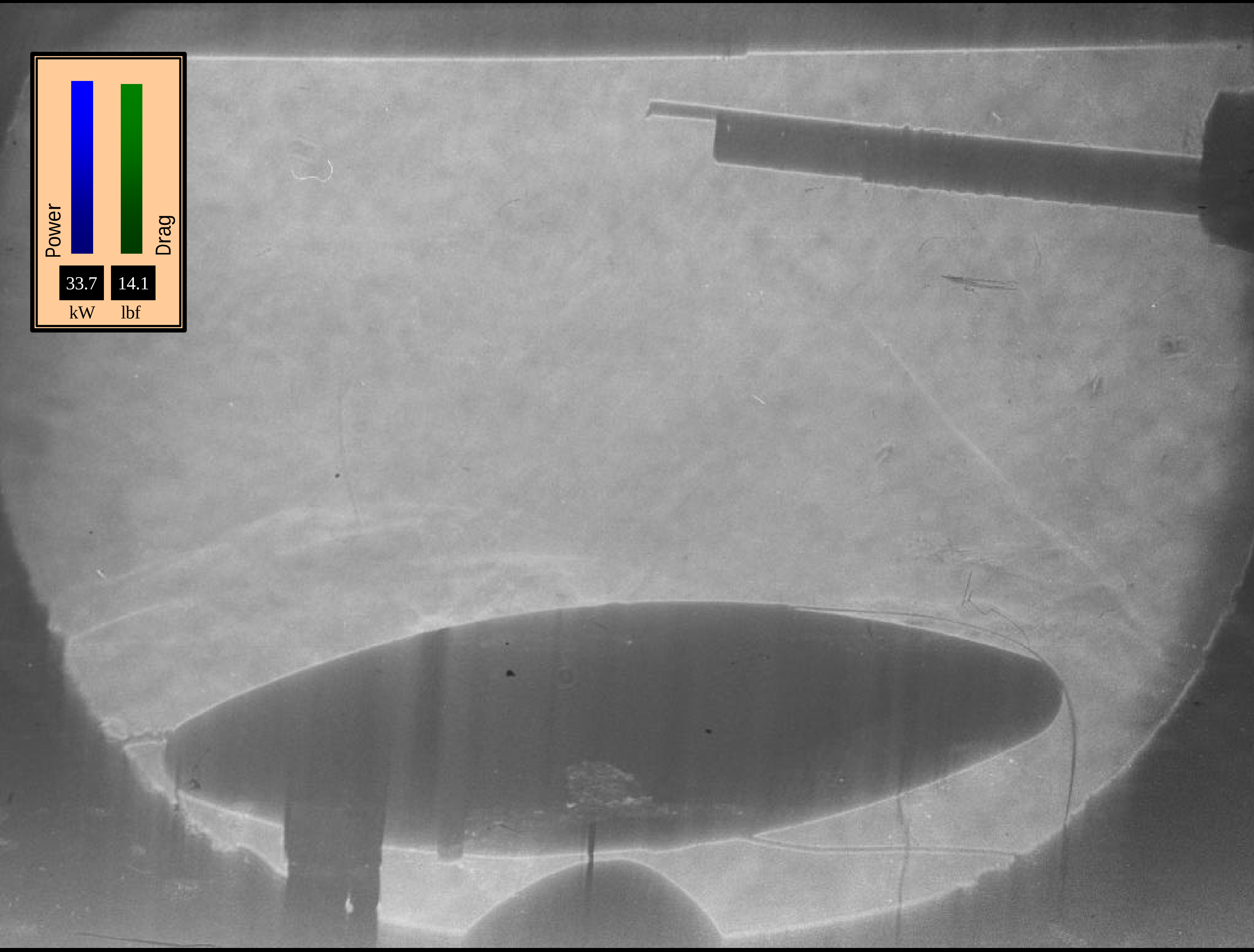
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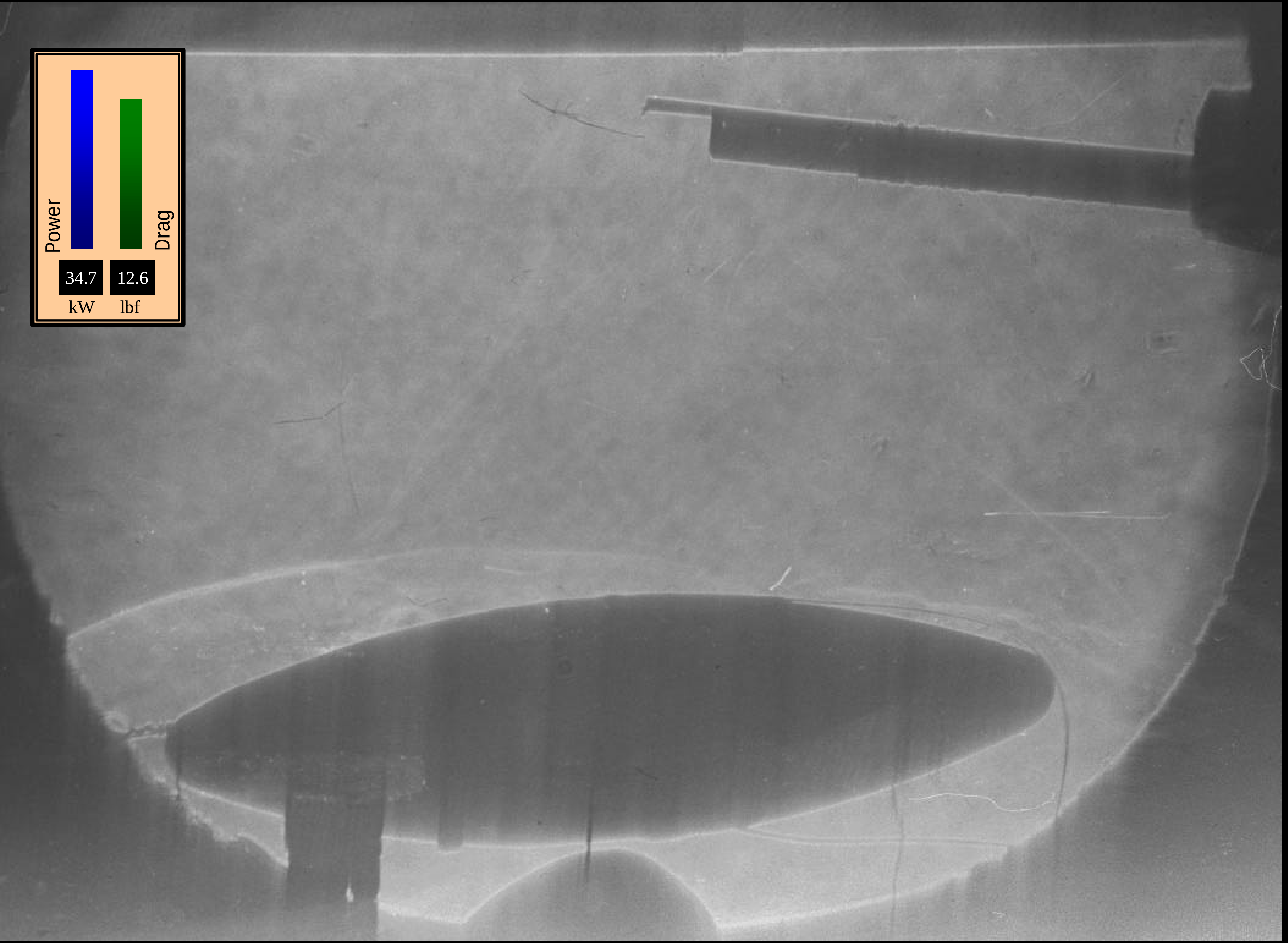
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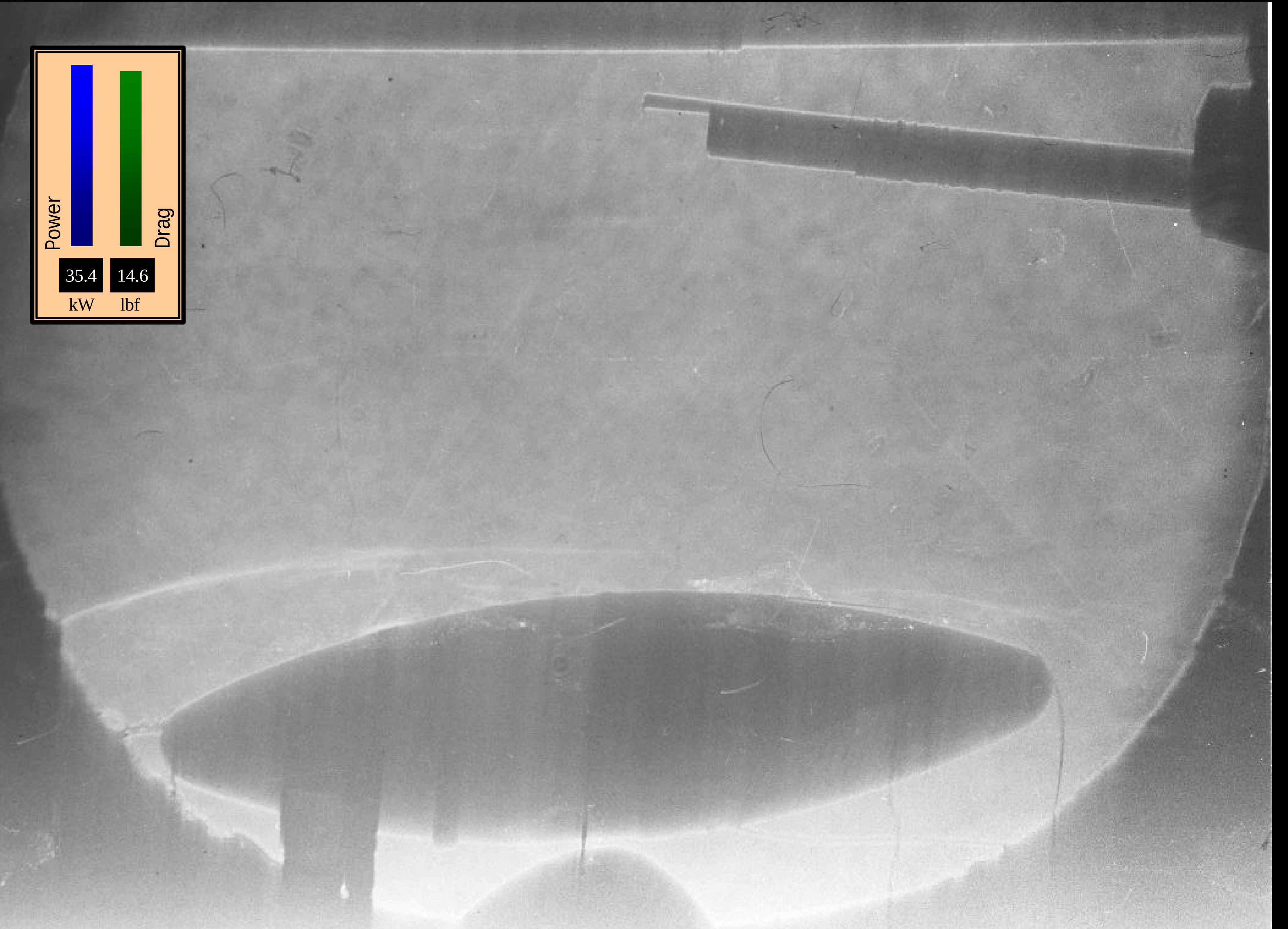
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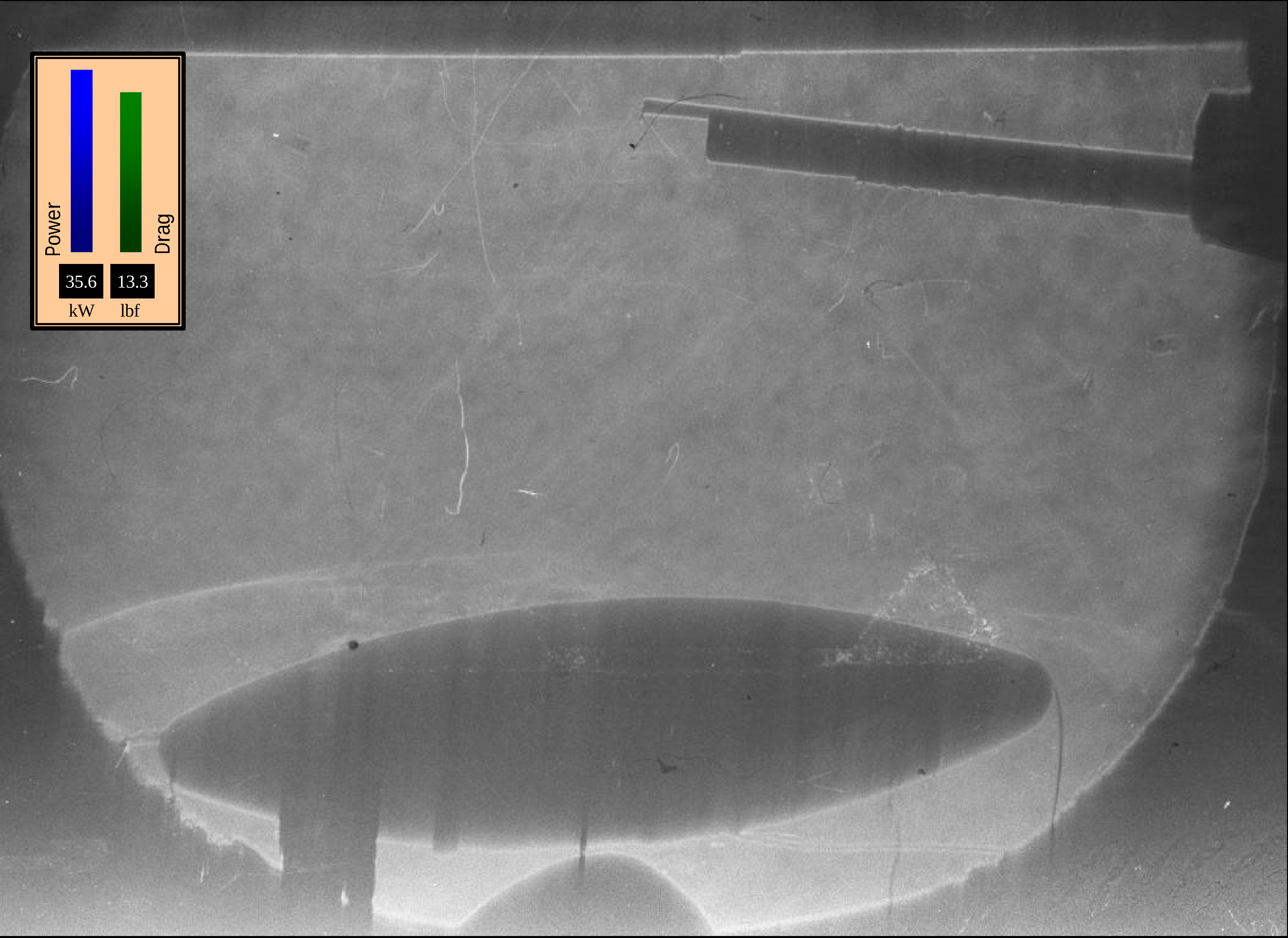
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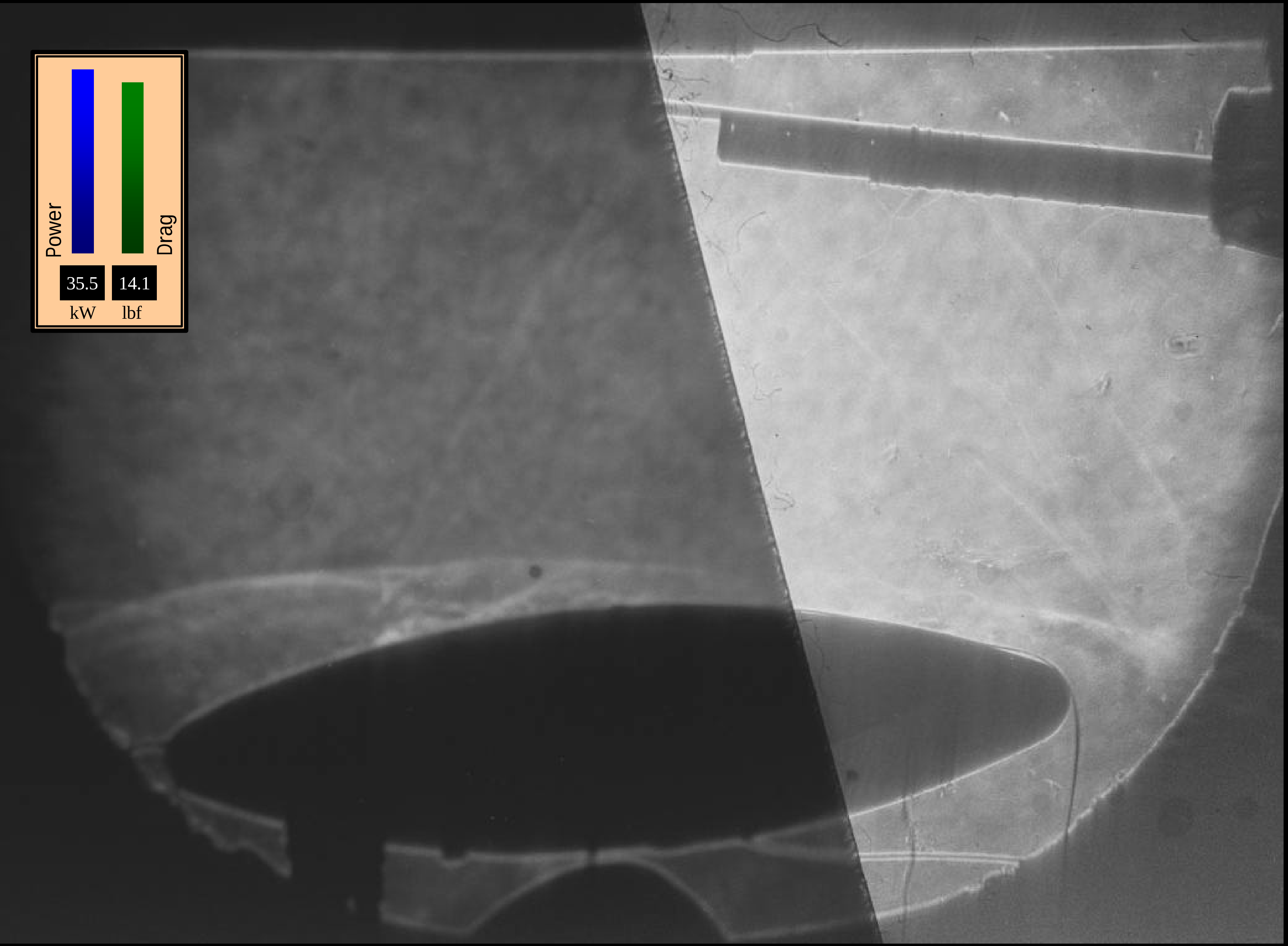
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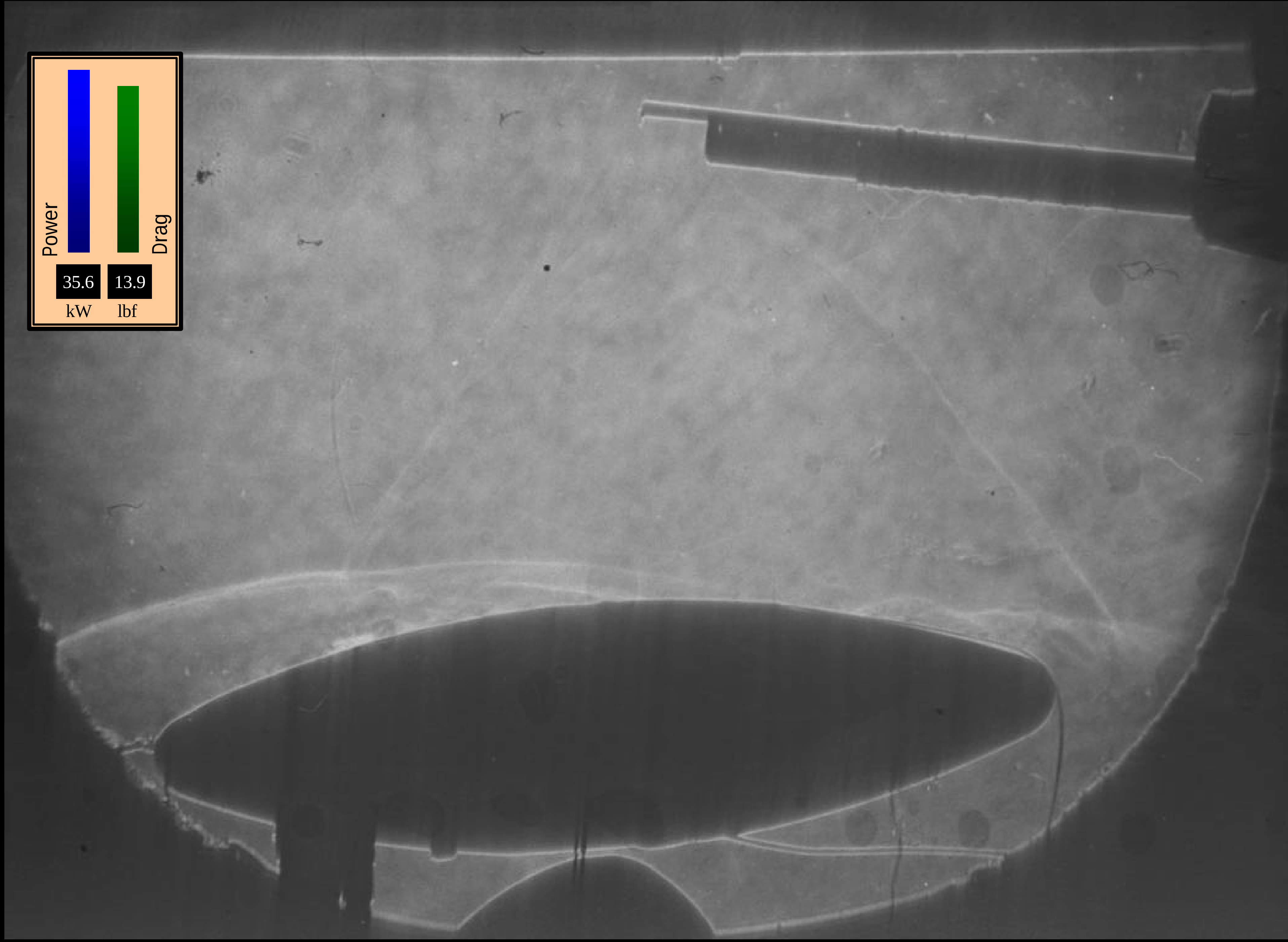
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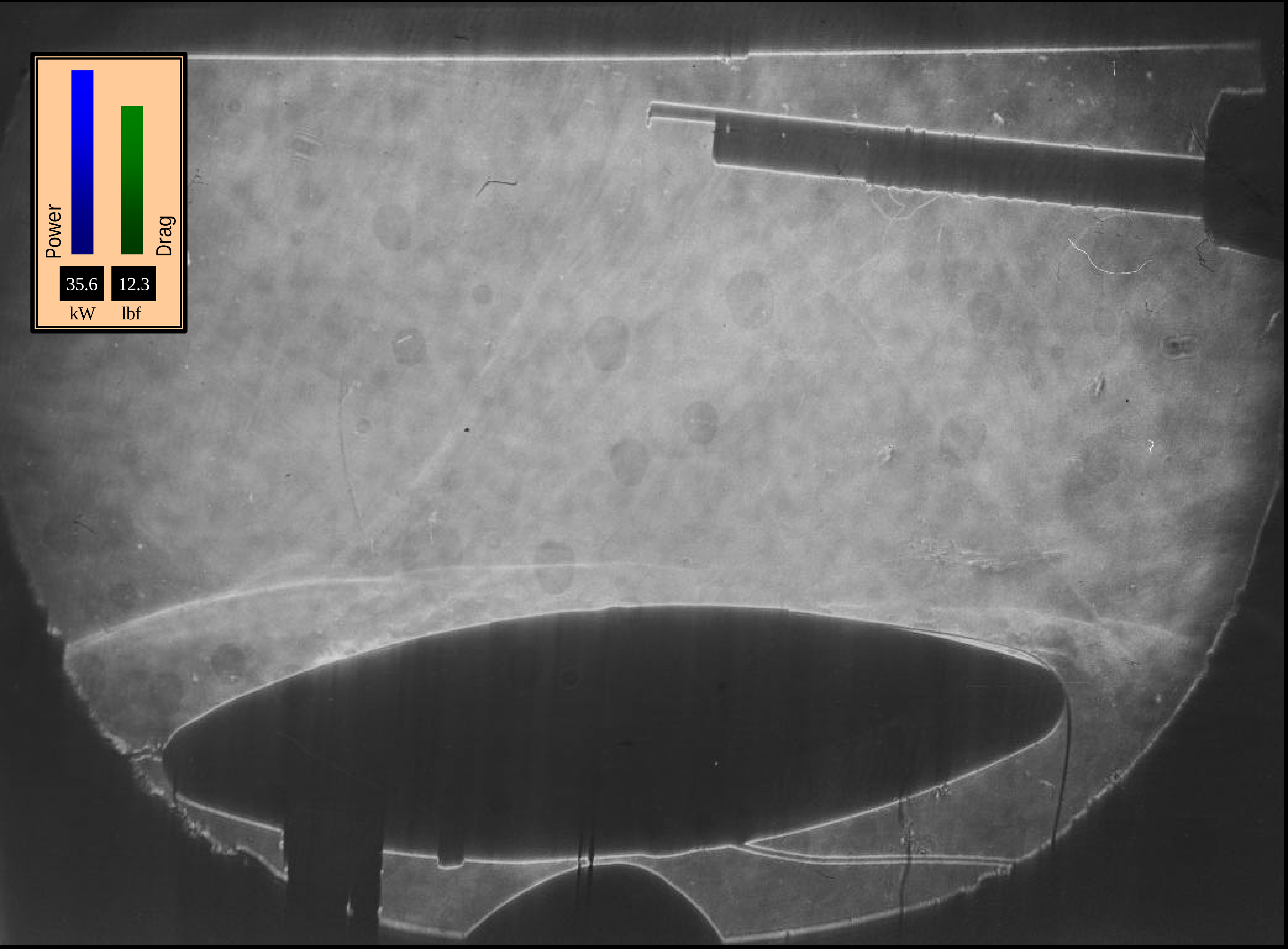
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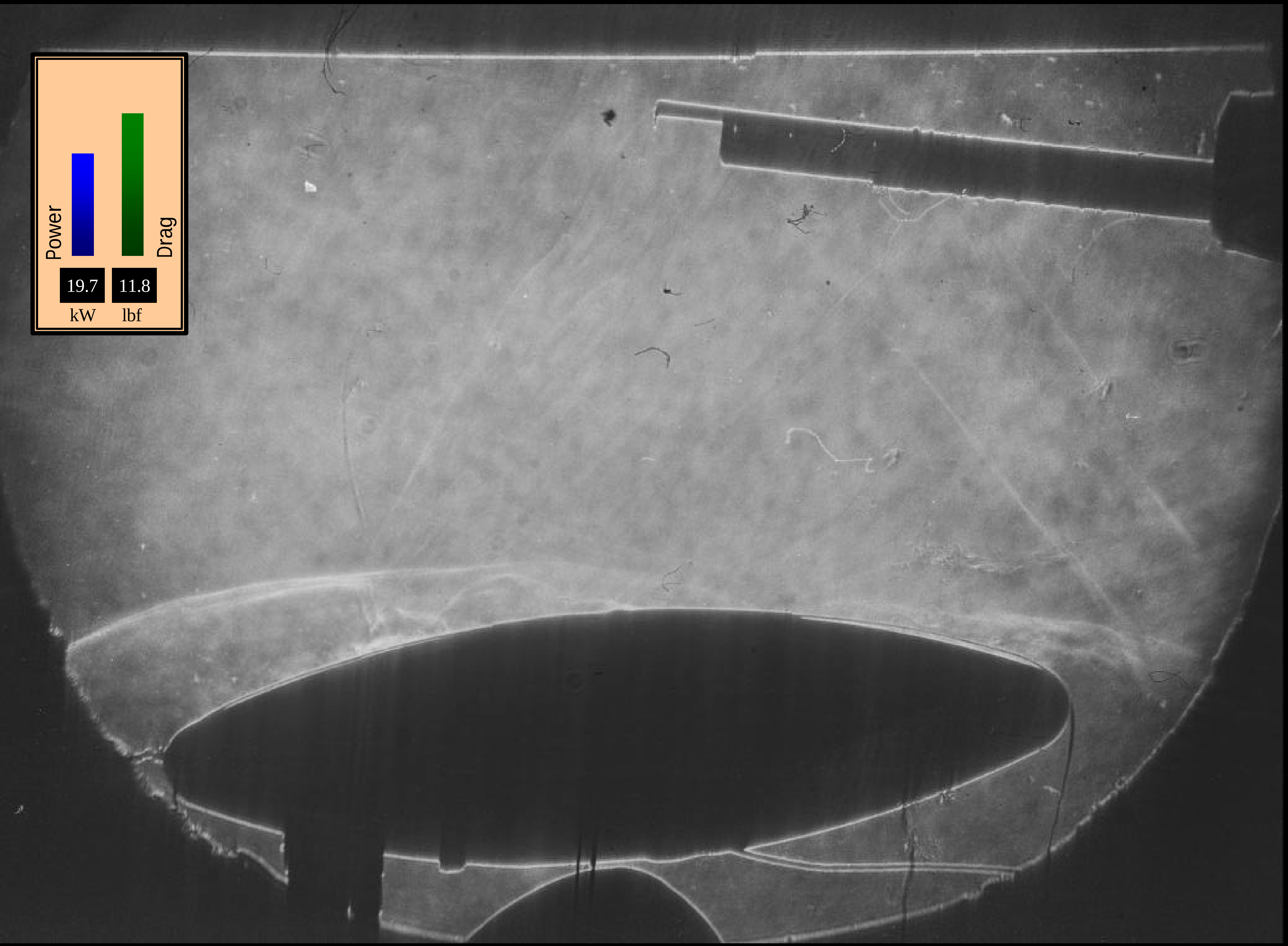
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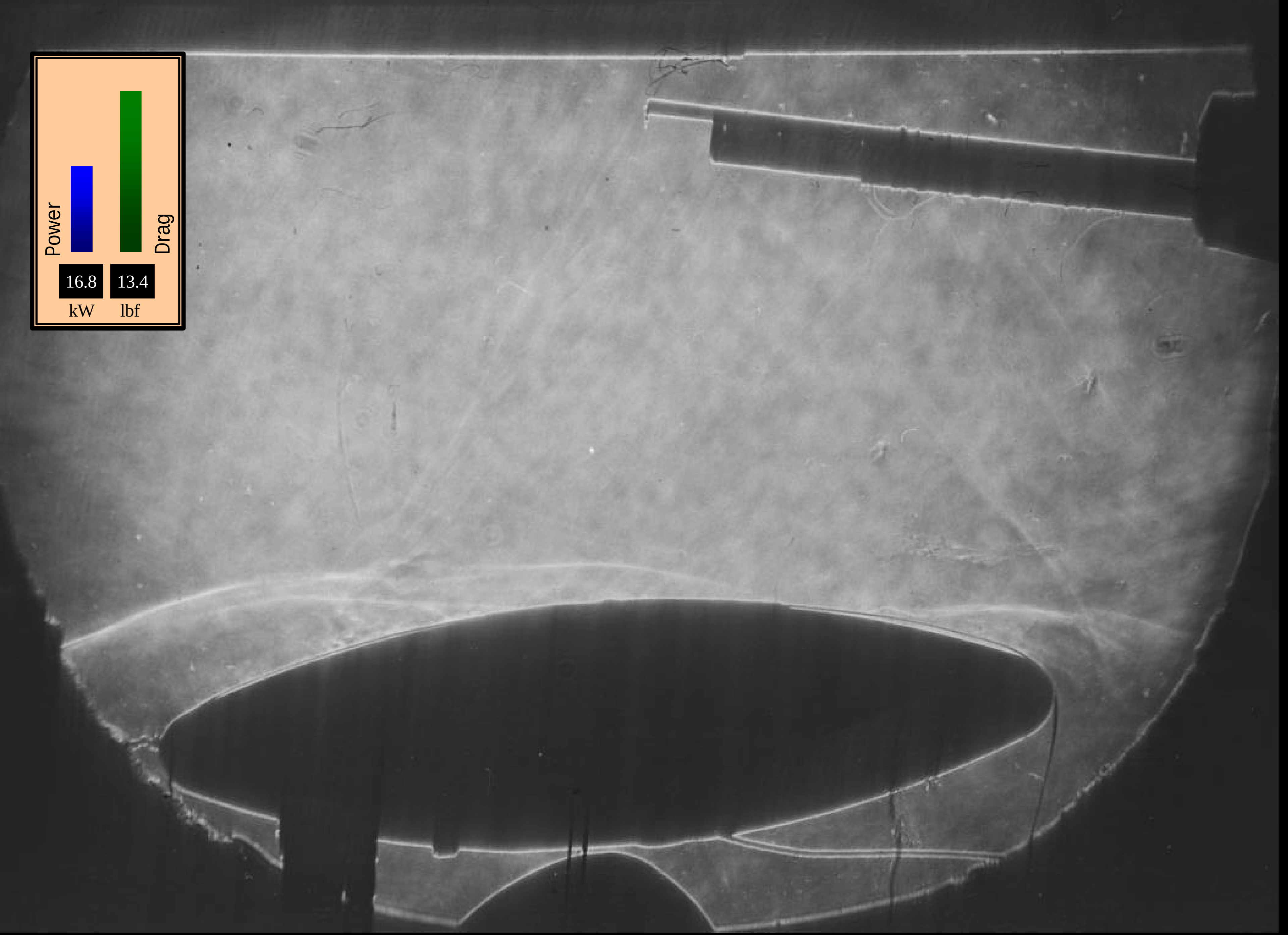

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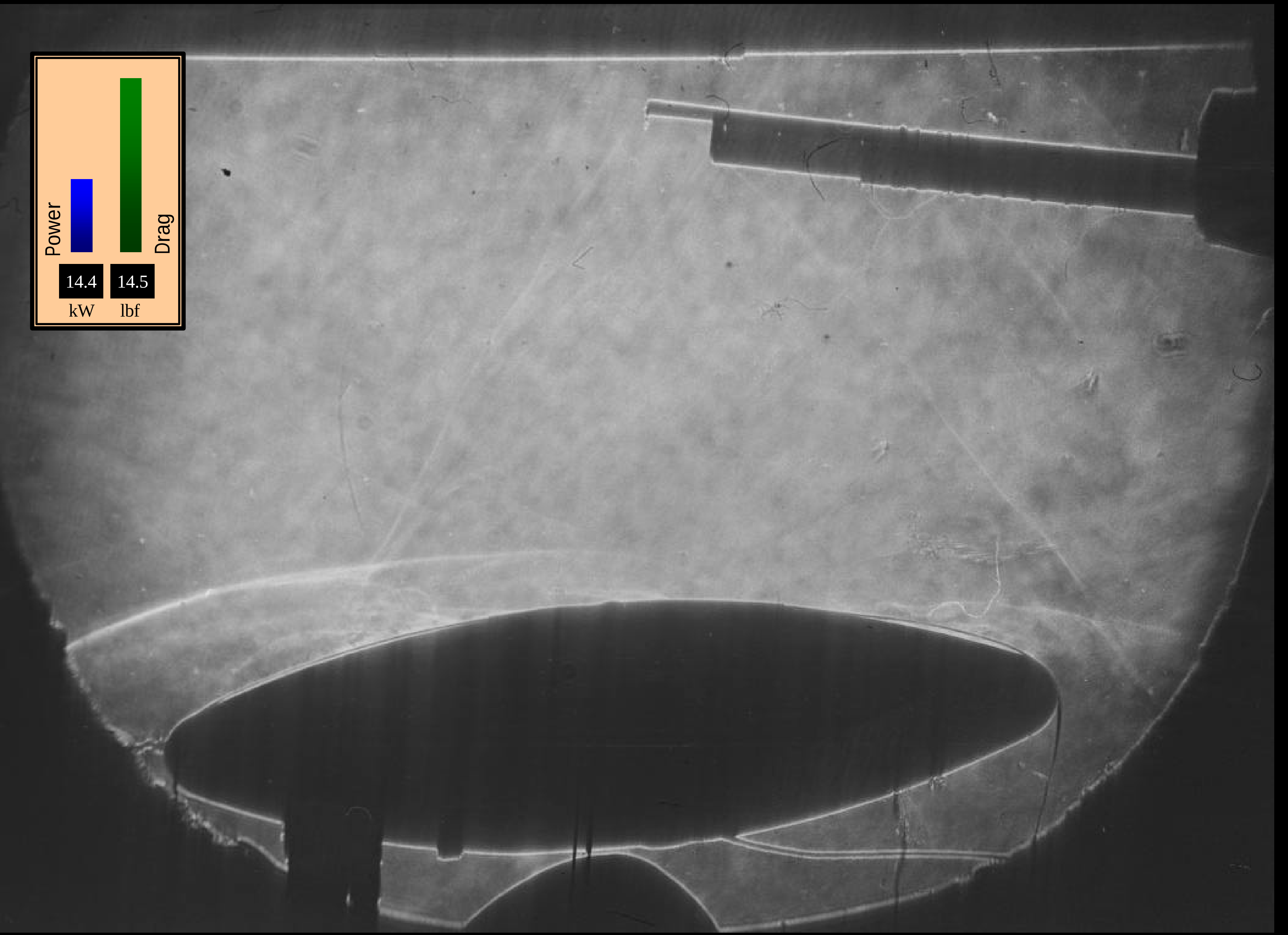
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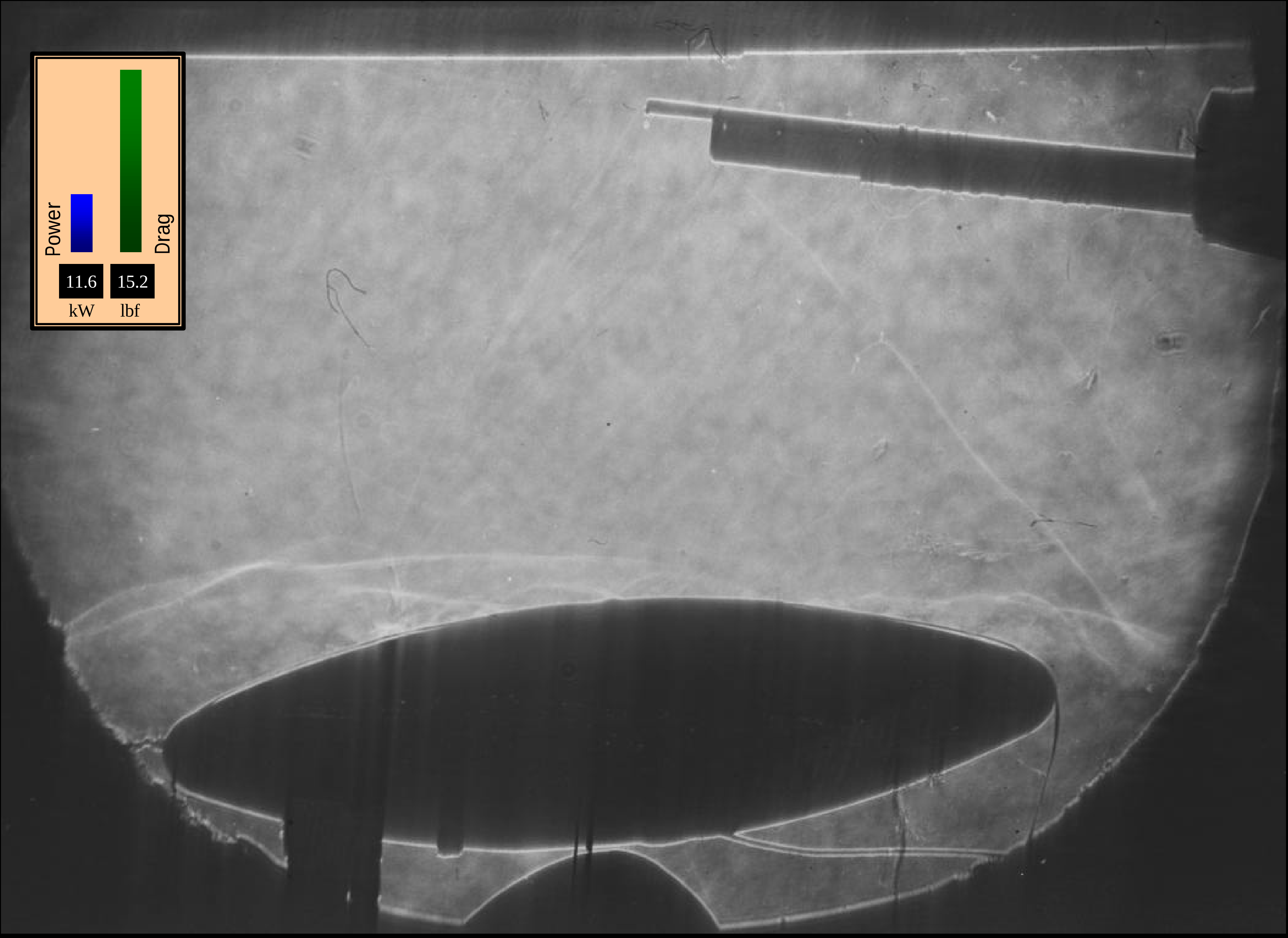
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